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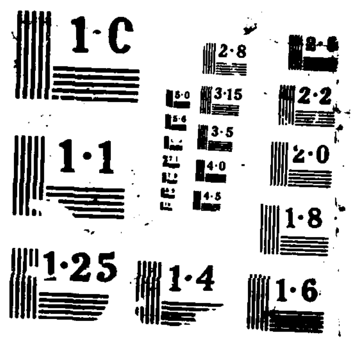

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AN EVALUATION OF THE METHODS FOR RESCUING EVA CREWMEMBERS AND RECOVERING EQUIPMENT DETACHED AND ADRIFT FROM THE SPACE STATION

THESIS

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Captain, USAF

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

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Masters of Science in Space Operations

Thomas Selinka, M.B.A.

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Tom Selinka

Table of Contents

Page

Acknowledgement ii

Table of Contents iii

List of Figures v

List of Tables vii

Abstract viii

I. Introduction 1
   Historical Background 2
   Future Prospects 6
   Specific Problem 8

II. Methodology 9
   Overall Problem Solving Framework 9
      Hall Morphology of Systems Engineering . . . 9
   Method for Determining The Problems Key Aspects . 11
      Concept Mapping 11
   Method of Evaluating Different Alternative
    Solutions 14
      Analytic Hierarchy Process (AHP) 15
   Summary 18

III. Problem Definition 19
   Extravehicular Mobility Unit (EMU) 19
   Orbital Mechanics 21
   Concept Map 29
   Summary 37

IV. Analysis 38
   Evaluation Criteria 38
   Analytic Hierarchy Process (AHP) Analysis . . . 41
      Principle of Decomposition 41
      Principle of Comparative Judgments 45
      Synthesis Principle 51
   Summary 55

V. Example Rescue/Recovery System 57
   Basic Configuration 57
   Short Range Subsystem 58
      Extravehicular Mobility Unit (EMU) with
       Jetpack 59
      Shepherds' Hook/Recovery Net 61
   Medium Range Subsystem 64
   Long Range Subsystem 66
   Summary 68

VI. Conclusion, Recommendations, And Issues . . . 70
Conclusions 70
Recommendations 72
Issues 74
Summary 75

A. Initial Pre-Concept Map Survey 77

B. Analytical Hierarchy Process Survey 80

C. Survey Results 89

D. Review of Contractor Proposed Solution Systems . 90

Bibliography 113

Vita 117

List of Figures

Figure		Page
1.	Space Station EVA Manhours Per Year	7
2.	Example Concept Map	13
3.	Space Station Coordinate System	24
4.	X-Axis Trajectory	25
5.	X-Axis Orbital Mechanics Effects Absolute Range, +x = 2 ft/sec	25
6.	Y-Axis Trajectory	26
7.	Y-Axis Orbital Mechanics Effects Absolute Range, +y = 2 ft/sec	27
8.	Z-Axis Trajectory	28
9.	Z-Axis Orbital Mechanics Effects Absolute Range, +z = 2 ft/sec	29
10a.	Consolidated Concept Map (Problem Definition)	31
10b.	Consolidated Concept Map (Value System Design)	32
10c.	Consolidated Concept Map (System Synthesis)	33
11.	AHP Hierarchy	42
12.	EVA Self Rescue Subsystem	60
13.	Space Station Supported Subsystem	63
14.	Medium Range Subsystem	66
15.	Long Range Subsystem	68
16.	Boom Extender	93
17.	MRMS	94
18.	Net Ejector System	95
19.	Rescue Tethered Unit	96

List of Figures (continued)

20. Enclosed Cherry Picker 97

21. Open Cherry Picker 98

22. Astrobot plus EEU 100

23. Telerobotic Vehicle 101

24. Prox-Ops-Vehicle 102

25. Free-Fly Independently Directed
Excursion Unit 103

26. MMU EVA Crew Rescue 104

27. Extravehicular Excursion Unit 105

28. Homing Unit Plus EEU 106

29. Man-In-Can 107

30. Manned Rover 108

31. Space Transportation System 109

32. CERV Systems 111

33. CERV Lifting Bodies 112

List of Tables

Table		Page
I.	Evaluation Criteria And Definitions	40
II.	Proposed Solution Systems	43
III.	Pairwise Comparison Matrix For The Evaluation Criteria	46
IV.	Matrix Weighting Factors	46
V.	Overall Evaluation Criteria Weights	47
VI.	Definitions	49
VII.	Long Range Generic System Types Preference Ratings	54
VIII.	Overall Ratings For Long Range Generic Systems	54
IX.	AHP Comparison Scale	86
X.	Survey Results	89

Abstract

This thesis is an analysis of the methods for EVA crew rescue and recovery of equipment detached and adrift from the space station. This top level analysis is aimed at identifying the proper direction to be taken in finding the solution system to the rescue/recovery problems. This analysis used the Hall morphology of systems engineering as the framework for the overall problem.

Within this approach, the technique of concept mapping was used to define the problem. Specifically, ten knowledgeable persons from Johnson Space Center were interviewed and a consolidated concept map of their understanding of the problems was generated. This map identified the key aspects and relationships between these aspects. Additionally, this map identified the evaluation criteria to be used in determining the preferred solution system to the problems.

The evaluation criteria of safety, response time, reliability, availability, and maintainability were used within the Analytic Hierarchy Process (AHP) to determine the preferred directions to take in solving the rescue/recovery problems.

Results of the analysis indicate that for short range rescue/recovery operations, both an EVA self rescue device

and a space station supported device are the preferred solution systems. For medium range rescue/recovery operations, an unmanned free-flyer is the ideal solution system. Finally, for long range operations, the Orbital Maneuvering Vehicle (OMV) is the preferred solution. The analysis also showed that the combination of all these preferred solutions is needed to completely solve the problems. To this end, the analysis provides an example of a comprehensive rescue/recovery system. Finally, the analysis identifies issues and recommends areas which require further analysis in order to fully understand and solve the problems of EVA crew rescue and recovery of equipment detached and adrift from the space station.

AN EVALUATION OF THE METHODS FOR RESCUING EVA CREWMEMBERS AND RECOVERING EQUIPMENT DETACHED AND ADRIFT FROM THE SPACE STATION

I. Introduction

In 1965 mankind took a bold step in the exploration of space. Specifically, for the first time, man, without the protection of a spacecraft, took a walk in space. These spacewalks later became known as Extravehicular Activities (EVAs). Perhaps the most exemplary of these EVAs were the ones performed by the various United States Skylab crews (1973-1974). These crews took the severely damaged Skylab vehicle and during extensive EVAs, fixed it to the point where it became inhabitable and operational. These EVAs directly led to the unqualified success of the Skylab missions (5:42).

The future holds the promise of the space station. Initial estimates are that astronauts can be expected to perform 2000 hours of EVA per year in support of this station (13:147). With safety in mind, the National Aeronautics and Space Administration (NASA) Space Station Office has asked various contractors to propose methods for rescuing EVA crewmembers. Additionally, NASA has asked for methods to recover detached and drifting equipment from the space station. In response to these questions, contractors

presented NASA with various proposed solution systems. NASA then performed an initial evaluation of these systems. To eliminate bias, NASA has requested an outside, impartial evaluation of these proposed solution systems. They are also looking for any additional systems which may be used to answer their questions (28). This thesis provides that impartial evaluation.

Historical Background.

In preparation for this evaluation, a brief look into the history of rescuing an EVA crewmember or recovering detached and adrift equipment needs to be accomplished. Due to the lack of information available on the Soviet space program, this historical flashback will center on the United States space program only.

The United States space program expanded into the area of extravehicular activity on June 3, 1965 when Lt Col Edward White took a 21 minute space walk from the Gemini 4 Spacecraft. Since that date, the U.S. has accumulated a total of 236 hours and 36 minutes of EVA experience in space (this figure does not include the 82 hours and 51 minutes of lunar EVA experience) (13:141,356). In this period, the U.S. has not had a single incident of an EVA crewmember becoming adrift or requiring rescue. However, the U.S. space program is prepared for such a contingency. Current operational planning calls for the Space Shuttle to rescue EVA

crewmembers if they become adrift (11:665). The probability of becoming adrift in space however, is not the only danger facing astronauts during EVA.

Space is a dangerous place. Several hazards have been identified which place an EVA crewmember in jeopardy. In a study by McDonnell Douglas Astronautics Company, four hazards were identified. These hazards are radiation exposure, mechanical dangers (micrometeoroids, space debris, and sharp corners/edges), atomic oxygen (which causes material degradation), and static charging (15:4-10 to 4-18). In fact, the entire realm of extravehicular activity is best summarized by Astronaut Pierre J. Thuot when he stated that "It's [EVA] risky business. Anytime you go out of the pressure vessel, now you're in your own little pressure vessel, it's risky business." (37).

As previously mentioned, one of the mechanical dangers is that of space debris. This hazard is one of the reasons why NASA is looking into systems which can also recover detached and adrift equipment from the space station. An example which points out this hazard occurred during the Skylab 2 mission of May 25, 1973.

The Skylab 2 crew of Conrad, Kerwin, and Weitz had tried for several hours to dock with the heavily damaged Skylab space station. It was finally decided that the crew should don their spacesuits, open the docking tunnel, and dismantle the docking probe. If these actions did not correct the

problem, an emergency return to earth was necessary. The EVA proceeded as planned until the point when the probe was dismantled. During this action, a nut (as in nut and bolt) floated off into space. The loss of this nut provided some anxiety to the crew; after successfully docking with the Skylab space station, it was questionable as to whether they could successfully undock without that missing nut. Luckily, all things worked out and Skylab 2 proved to be one of the most successful of the Skylab missions (13:84).

This example serves to point out two key areas about the recovery of adrift equipment. First of all, it points out that an object as small as a nut can be critical to the success of a mission. Thus, the operational value of adrift equipment can drive the requirement for recovery. Secondly, this example shows that equipment does become detached, can float off into space, and could create a hazard.

In addition to directly affecting the mission, the lost nut also posed a long term hazard in the form of space debris. Because of it's small size, the nut may not seem like that great a hazard, but closer analysis shows that it is indeed a substantial hazard due to its kinetic energy. For example, a 7.3 gram nut that floats away from the space station, which is at an altitude of 292 miles (470 km), will have a kinetic energy of approximately 212,400 Joules (its velocity is approximately 4.74 miles/sec). Compare this to a typical .30 caliber bullet. The bullet also has a mass of

about 7.3 grams (110 grains) and a muzzle velocity (depending on load) of about 3,000 ft/sec. This gives the .30 caliber bullet a kinetic energy of 3,050 Joules (30:28). Thus, the kinetic energy of the floating nut is approximately 70 times the kinetic energy of the speeding bullet. The damage potential of the nut is now quite apparent.

The U.S. Space Program has had a history of equipment becoming detached and adrift from spacecraft during EVAs. The example of the Skylab 2 mission pointed this out, but this problem has occurred since the beginnings of the U.S. EVA history. In fact, the first piece of equipment to be lost occurred during the historic Gemini 4 mission when a glove floated out of the spacecraft. Additionally, during the Gemini 9 mission, a camera managed to float away. The general conclusion from the Gemini program regarding equipment losses during EVA was that if it wasn't tied down, it would float away (39). This conclusion led to the practice of tethering equipment to the spacecraft as is currently done in the space shuttle missions.

However, the space shuttle missions have had their own problems with equipment becoming detached and floating away, this in spite of the emphasis placed on tethering. Specifically, during the 41B Mission a foot restraint became detached and floated away. However, it was recovered by maneuvering the space shuttle to a position where Astronaut Bruce McCandless could reach out and grab it (14). This was

probably the first time a spacecraft was maneuvered solely to recover detached equipment. The shuttle missions of 51A and 51C also had problems of equipment floating away, but in these cases, the equipment was not recovered. The 51A Mission had several screws float off into space (39). Likewise, the 51C Mission had a power wrench drift away (2). Thus, the problem of equipment becoming detached and adrift remains. This problem has happened in the past and it most certainly will occur in the future.

Future Prospect.

The initial on orbit construction of the space station is expected to begin in 1994 (35:2). EVA is going to be an integral part of this construction. EVA will also be an integral part of the space station's operations. A McDonnell Douglas study in 1986 (prior to the Challenger tragedy) indicated that EVA at the space station will fall into two categories: EVA for user missions (satellite support) and EVA for Space Station Maintenance (15:2-17). This study also projected the total EVA manhours per year that the space station would support. These manhours are shown in Figure 1.

It should be pointed out that the number of EVA manhours being projected for the space station during its first year of operations is six times the total US EVA experience. With this amount of manhours, it can be expected that equipment will become detached and require recovery (28). The need for

equipment recovery may occur during any phase of the space station's operations. However, the greatest need for a recovery system may well occur during the construction of the space station itself (3). With this in mind, the development of a system to rescue EVA crewmembers and recover detached and adrift equipment from the space station becomes time critical. Such a system should be in place for space station construction. Naturally, in order to have a system in place, a decision as to what system will best do the job needs to be made. This thesis will help address that decision.

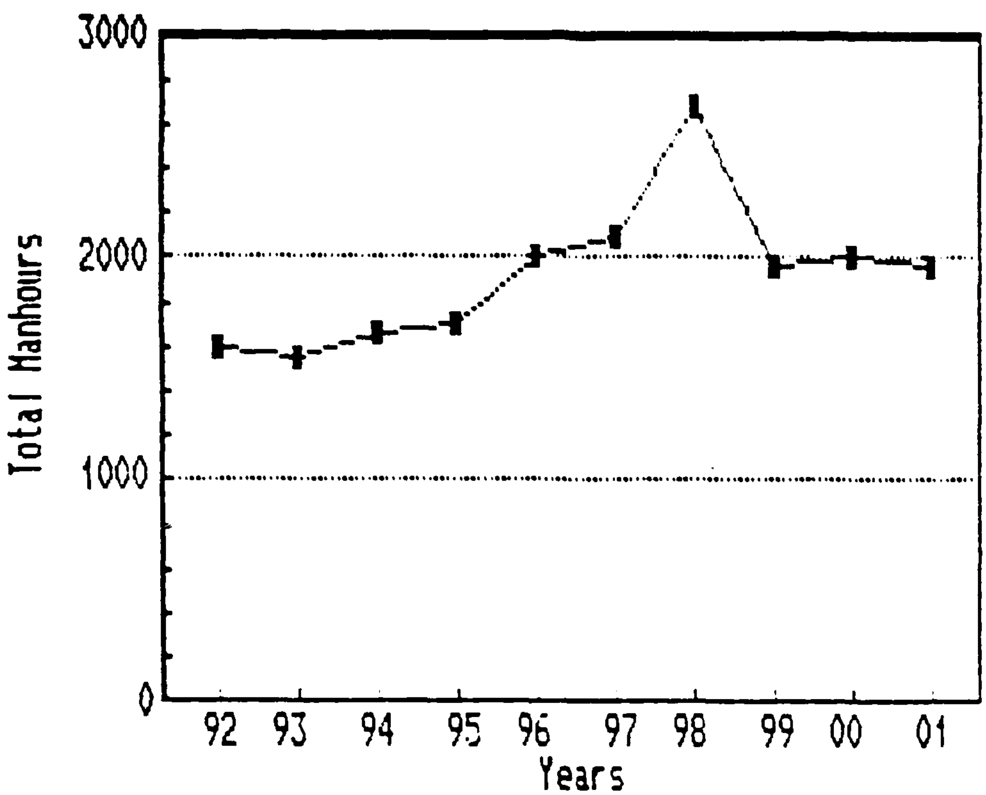


Fig. 1. Space Station EVA Manhours Per Year (15:2-17)

Objective Statement.

The objectives of this thesis are to: 1) develop a methodology for evaluating solution systems to the problems of EVA crew rescue and equipment recovery, 2) apply that methodology to the NASA provided contractor proposed solutions, 3) develop, if necessary, other conceptual solution systems, and 4) provide direction as to which generic solution system types best solve the problems.

II. Methodology

To meet the objective of this thesis, a logical approach for evaluating alternative solutions to the problems of EVA crew rescue and equipment recovery must be developed. Several key areas have been identified within the development of this approach. Specifically, three areas require in-depth knowledge in order to fully understand the methodology this thesis will follow. These areas are: 1) developing an overall problem solving framework, 2) developing a method to determine the key aspects of the problem and, 3) developing a method to evaluate the different alternatives.

Overall Problem Solving Framework.

The first area requiring an in-depth understanding is that of determining an overall problem solving framework within which the problems of this thesis can be answered. Due to the fact that the problems require investigation into technology and systems development, it is logical that some type of system engineering approach be considered for the overall problem solving framework. This thesis will use the Hall morphology of systems engineering.

Hall Morphology of Systems Engineering. This approach deals with the three dimensions of systems engineering. According to Hall, these dimensions are time, logic, and knowledge. Hall states that the dimension of time represents

"a course structure depicting a sequence of activities in the life of a project from inception to retirement" (10:156). Hall defines the logic dimension as being the problem solving procedure of his morphology. This dimension logically progresses from problem definition to a solution. The seven steps in this dimension are as follows: 1) problem definition, 2) value system design (develop objectives and criterion), 3) systems synthesis (collect and invent alternatives), 4) systems analysis (deduce consequences of alternatives, 5) optimization of each alternative (iteration of steps 1-4 plus modeling), 6) decision making (application of value system) and 7) planning for action (to implement the next time phase) (10:157). The third dimension, knowledge, defines the discipline, profession, or technologies required to solve the problem (10:156). Sage points out that these dimensions provide structure to systems engineering when applied to a specific problem (34:6).

In the case of this thesis, there are two related problems, the problems of EVA crew rescue and equipment recovery. When the Hall morphology of systems engineering is applied to these problems, an overall framework for their solutions quickly emerges. The time dimension shows that these problems are in the project planning and preliminary design phase of a project's life. This means there are many alternatives to solve the problems, but not much technical information is available on these alternatives. The logic

dimension describes the path to follow in solving the problems. For this thesis, portions of the problem definition and systems synthesis steps have been provided by NASA. Finally, the knowledge dimension shows that the areas of astrodynamics, life support, and operations research will play an important role in solving the problems. For these reasons, the Hall morphology of systems engineering has been chosen as the overall framework within which to solve the problems.

Method for Determining the Problem's Key Aspects.

The second area of methodology is that of developing an approach to determine the key aspects of the problems associated with EVA crew rescue and equipment recovery. One technique which shows great promise in this area is that of concept mapping.

Concept Mapping. Developed in the early 1980s as an educational tool, concept mapping has the unique ability to capture an expert's conceptual structure of a problem (17:Ch3,p10). Concept mapping does this by developing a visual representation which shows how the various aspects of the problem are linked together. These visual representations are known as concept maps and they provide three major benefits. These benefits are: 1) the identification of a small number of key ideas within a subject, 2) a visual road map of the subject, and 3) a

schematic summary of the domain of interest (17:Ch3,p3).

Perhaps the best way to fully explain a concept map is to provide an example. The example map (Figure 2) examines the area of judging the quality of meat and was prepared for a course teaching meat science (9:Fig 2.5). This map shows that various concepts within the subject are connected. This connection is done through the use of linking words. For example, the concepts of "Meat Quality" and "Judging" are linked together by the connector "can be." This forms the complete thought of "Meat quality can be judged." The power in concept mapping is that several complete thoughts can be linked together. For example, the concept of "Criteria" is linked to the concepts of "Color," "Texture," "Firmness," and "Marbling." These links not only show the relationships between the concepts, but due to their position, also indicate that this is a hierarchical relationship. Other links show lateral relationships between concepts. An example of this is the relationship between the concepts of "Grass" and "Grain" in that both develop "Intermuscular Fat." By examining the relationships in this map, someone who does not know anything about the subject of judging meat quality can gain a good understanding of the subject.

Concept maps are developed through face-to-face interviews. In these interviews, the person doing the interview tries to capture the conceptual knowledge of the person being interviewed by generating a concept map of the

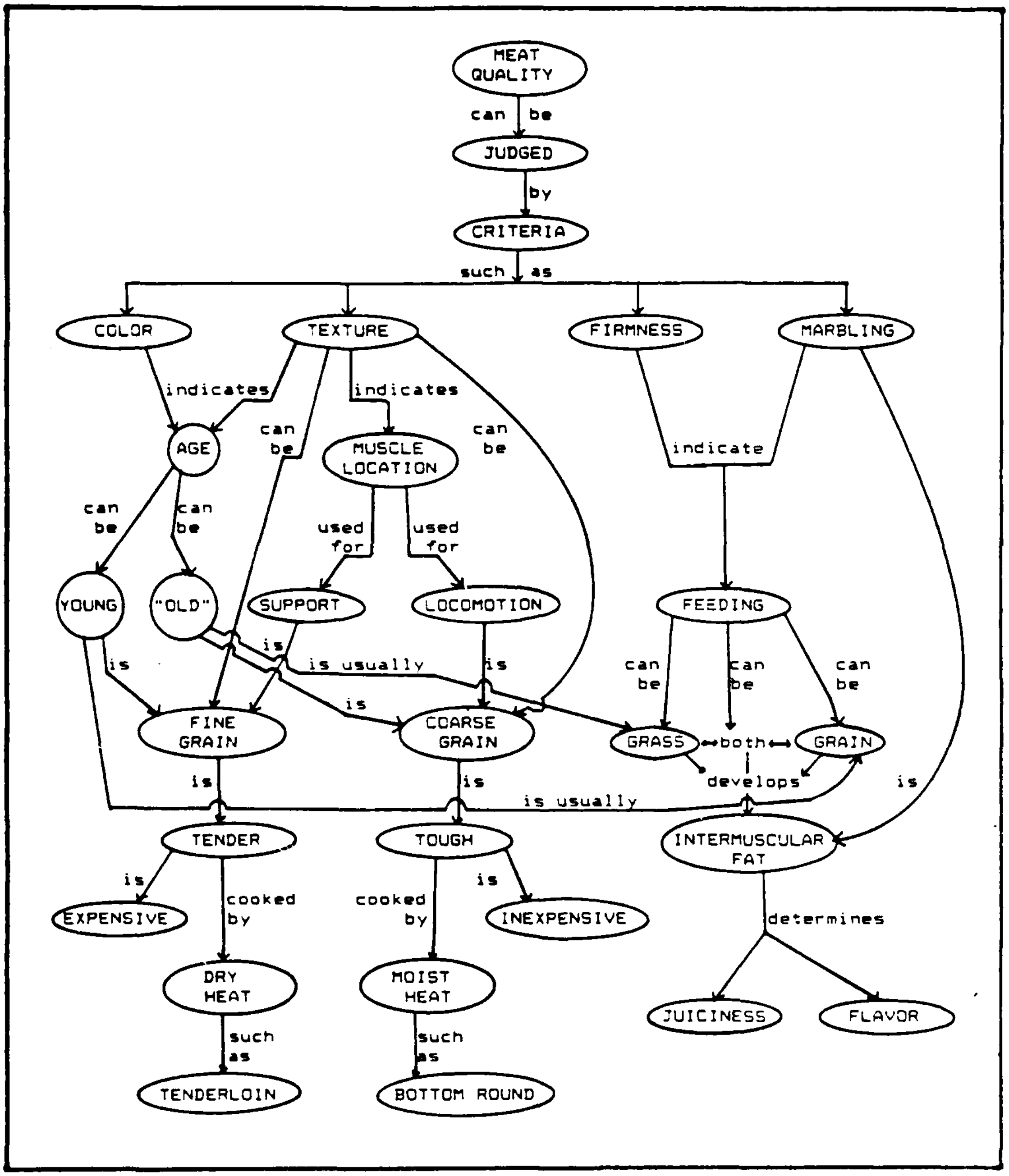


Fig. 2. Example Concept Map (9:Fig 2.5)

subject being discussed. There is a lot of interface and feedback between the interviewer and the person being interviewed during the development of the concept map. Because of this, care must be taken to insure an effective interview. In his thesis, Capt Mike McFarren details the three steps of effective concept mapping interviews. These steps are 1) scheduling the interview, 2) setting up the environment for the interview, and 3) managing the interview (17:Ch4,pp5,6). All of these steps are aimed at the goal of capturing the expert's understanding of the problem and recording this understanding in the form of a concept map. Perhaps the best advice on developing a concept map was provided by Capt McFarren when he said that concept mapping is an art which needs to be practiced (16). By practicing this art, the ability of the interviewer to recognize concepts, successfully link them together, and form a comprehensive concept map becomes an acquired skill.

In this thesis, the problems of EVA crew rescue and equipment recovery are rather complex. There are many aspects to the problems and these aspects often relate to each other. Because of this, concept mapping appears to be a viable method for capturing the essence of the problems. Thus, this technique was used in this thesis.

Method of Evaluating Different Alternative Solutions.

The third area required in the development of a

methodology is that of developing an approach to evaluate the different alternatives which solve the problems. This approach was used in the systems analysis step of the Hall morphology of systems engineering. The analytical approach which was used in this thesis is the Analytic Hierarchy Process (AHP).

Analytic Hierarch Process (AHP). As problems become complex with different related factors and with many alternative solutions, the relationships between these factors and alternatives often become blurred. According to Saaty, what is needed is "to organize our problems in complex structures which allow interactions and interdependence of factors but which also allow us to think about them one or two at a time" (33:140). Analytic Hierarchy Process is a framework which allows problems to be structured this way.

The three principles upon which AHP is founded are decomposition, comparative judgments, and synthesis of priorities (33:141).

The principle of decomposition involves decomposing a complex problem into a hierarchy. This hierarchy is structured such that each level has only a few manageable elements and that these elements capture the major components of the problem (41:642). These major component elements are then decomposed into their representative sub-elements. The hierarchy has two roles. The first role is to transform a complex problem into one which can be easily understood. The

second role is to break the problem into functionally similar levels (29:238). This breakdown allows for the next principle to be applied to the problem.

The principle of comparative judgments is one of determining priorities. Basically, this principle calls for the decision maker to evaluate each set of elements within a level (in a pairwise fashion) with respect to an element in the next higher level (38:62). These pairwise comparisons indicate the relative importance (weight) of the elements within a level. These priorities are formulated in a comparison matrix (33:141). After all the elements on all the levels are prioritized, the synthesis of the priorities can then begin.

According to Vargas and Dougherty, the synthesis principle calls for the generation of composite priorities for each element. This generation involves a level-by-level aggregation of the pairwise comparisons. The procedure used to aggregate is through the use of eigenvalues or that of calculating the geometric mean (38:65). The resulting composite priorities represent the decision maker's judgments as to the relative importance of the elements in the hierarchy. This principle is important for two reasons. The first reason is that once all the aggregation is completed, the composite priorities for the lowest level of the hierarchy usually point to the preferred alternative solution. Secondly, this process allows for a consistency

check of the weight factors used in the analysis (33:142).

As seen in this discussion, AHP is a simple yet powerful approach to solving complicated problems. AHP is conceptually simple. It follows the basic divide and conquer principle. However, AHP also allows for the complexities of a problem to be tackled. Despite all these good qualities, AHP is not without criticism. One of the major problems of AHP is that the technique does not guarantee the validity of the weights used in the analysis (12:728). The reason for this problem is that the weights are based on the subjective reasoning of the decision maker. The decision maker is human and can change his/her mind. However, AHP allows for this inconsistency as part of its theory (33:144). AHP also suffers the problem of defining exactly who the decision maker actually is. In the case of multiple decision makers, Saaty recommends that the aggregate weight be determined by taking the geometric mean of the individual weights (33:151).

In spite of these problems, AHP appears to be a reasonable approach to the problems of EVA crew rescue and equipment recovery. This reasonableness is due to the fact that the approach is relatively simple to understand and that the breaking down of the problem into its hierarchy tends to help with the definition of the problem. This ability to better define the problem can often reduce the perceived complexities of the problem.

Summary.

This section has developed the methodology that was used in the development of solutions to the problems of EVA crew rescue and recovery of detached and adrift equipment from the space station. Specifically, these problems were examined in the light of the Hall morphology of system engineering. The technique of concept mapping was used in the problem definition and value system design steps of this morphology. Also, the Analytic Hierarchy Process (AHP) was used to provide the systems analysis of the proposed solutions to these problems. Thus, this thesis demonstrates the techniques of concept mapping and AHP within the Hall morphology of system engineering framework.

III. Problem Definition

As indicated in the literature review, the problems of EVA crew rescue and recovery of detached and adrift equipment from the space station are still in the project planning and preliminary design phase of the project's life. During these phases initial system concepts are developed based on a thorough understanding of the problem. The concept mapping activity helps explain the complexities and relationships within the problems. However, a little technical background into the areas of the Extravehicular Mobility Unit (EMU) and orbital mechanics is required to fully understand the problems.

Extravehicular Mobility Unit (EMU).

When an astronaut is performing EVA, the Extravehicular Mobility Unit (EMU) is providing two essential functions for the astronaut. The first function is to provide a highly mobile enclosure (space suit) which allows for tasks to be performed in space. The second function is that of life support. This function consists of providing a controlled pressure environment, providing clean oxygen for breathing, maintaining temperature control, and providing for waste management (4:3). In the current EMU, these life support functions are all contained within the unit (which resembles a backpack). It is expected that the space station EMUs will

be similarly configured (15:3-1). This configuration allows for EVA without being tied to umbilical cords which have provided these life support functions in the past.

The problem with this type of system configuration is that the EMU can only carry a limited amount of the gasses and fluids which are consumed by an astronaut to sustain life. The most critical of these consumables is oxygen. The current EMU has an oxygen supply which will last for a maximum of seven hours (24:1.2-3). Current studies for the space station's EMU project approximately a nine hour oxygen supply (15:3-3;20:4). With this limit on the amount of oxygen available, EVA crew rescue becomes extremely time critical. If crew rescue is required during the latter portions of an EVA, there will be a finite limit on the oxygen available to the crewman requiring rescue. The worst scenario for rescue would occur at the end of a typical EVA when there is only 86 minutes of oxygen remaining in the EMU (21:7). The amount of consumable oxygen thus sets a limit on the time available for EVA rescue. A second factor which could cause a time constraint for rescue is that of a malfunctioning EMU.

Like any piece of hardware, the EMU is susceptible to malfunctions. Past history has shown this. On the fifth space shuttle mission, scheduled EVAs were cancelled because of space suit malfunctions. One of these malfunctions involved the EMU pressure regulator providing lower than the

desired 4.3 psi. The other malfunction involved an improperly operating fan. This fan is needed to circulate air for breathing and supplementary cooling to the astronauts (7:73,78). Although neither of these malfunctions would have been immediately life threatening had they occurred during an EVA, they could have caused an unscheduled termination of the EVA. The space station EMUs are expected to be a higher pressure, more advanced version of the current EMU (15:4-2 to 4-3). Malfunctions in this newer model could also cause the termination of EVA. Although these malfunctions may not cause the problem of drifting EVA crewmembers, they will impact on the rescue operations for those adrift crewmembers. As such, the EMU needs to be acknowledged as a player in the problem.

With this technical background about the EMU complete, it is now time to move into the area of Orbital Mechanics and its impacts on the problems.

Orbital Mechanics.

The orbital mechanics of objects departing the space station play an important role in defining the problems. The initial velocity and initial direction of an object departing the space station determine the object's orbital characteristics. These characteristics drive the rescue or recovery scenario. Thus, an examination of these initial velocities and initial directions needs to be conducted in

order to fully understand their impact on the problems of EVA crew rescue and equipment recovery.

In January of 1987, NASA conducted a study on the dynamics of EVA crewmembers inadvertently separated from the space station. This study involved the determination of initial velocities and rotation rates associated with various push-off scenarios while in a weightless environment. The push-off scenarios consisted of imparting a force to a stationary structure by pushing off with one hand, two hands, one leg, or both legs and measuring the resulting velocities. The weightless environment was simulated by flying a KC-135 through a trajectory which simulates weightlessness. Two important results were obtained from this study. The first was that the initial velocity of separation averaged to be 2.2 ft/sec for a suited crewman. The second result indicated that there is always some type of tumble associated with these push-offs (23:7). This tumble is due to the fact that it is almost impossible to impart a push-off force directly through the crewman's center of mass. Using the results of this study, initial orbital characteristics were determined for an EVA crewman separating from the space station.

All the orbital characteristics studied use the space station as the reference point for the calculations. This is done because the problems of EVA crew rescue and equipment recovery call for the return of the object/crewman to the space station. As such, a coordinate system (Figure 3) is

established with the space station at the origin, the x-axis pointing in the direction of the space station's velocity vector as it orbits the earth, and the z-axis points in a direction perpendicular to the x-axis but directly away from the earth's center of gravity. Thus, a measurement of the distance to the earth is found in the minus z direction. The y-axis is perpendicular to both the x-axis and z-axis and indicates the direction of a plane change. Calculations of orbital characteristics are based on the space station in a circular orbit at an altitude of 292 miles with an orbital period of 94 minutes. The space station is also assumed to be always orientated in the same direction with respect to the earth (19:19,25). With these assumptions, orbital characteristics are calculated for an initial velocity of 2 ft/sec for an object in the purely x, y and, z-axis directions.

With an initial velocity of plus 2 ft/sec in a pure x-axis direction, the objects orbital characteristics change the original circular orbit to that of an elliptical orbit (Figure 4). This orbital change causes the object to drift away from the space station at a surprising rate. In fact, at the end of 20 minutes, the object is approximately 2700 ft away from the space station (in the x direction) and moving at a relative velocity of 7.2 ft/sec (20:4). At the end of one orbit (94 minutes) the object will be approximately 34,000 ft (6.44 miles) away from the space station and

departing at an ever increasing rate (25:4). Figure 5 shows the relationship between absolute range and time due to this pure x-axis initial velocity.

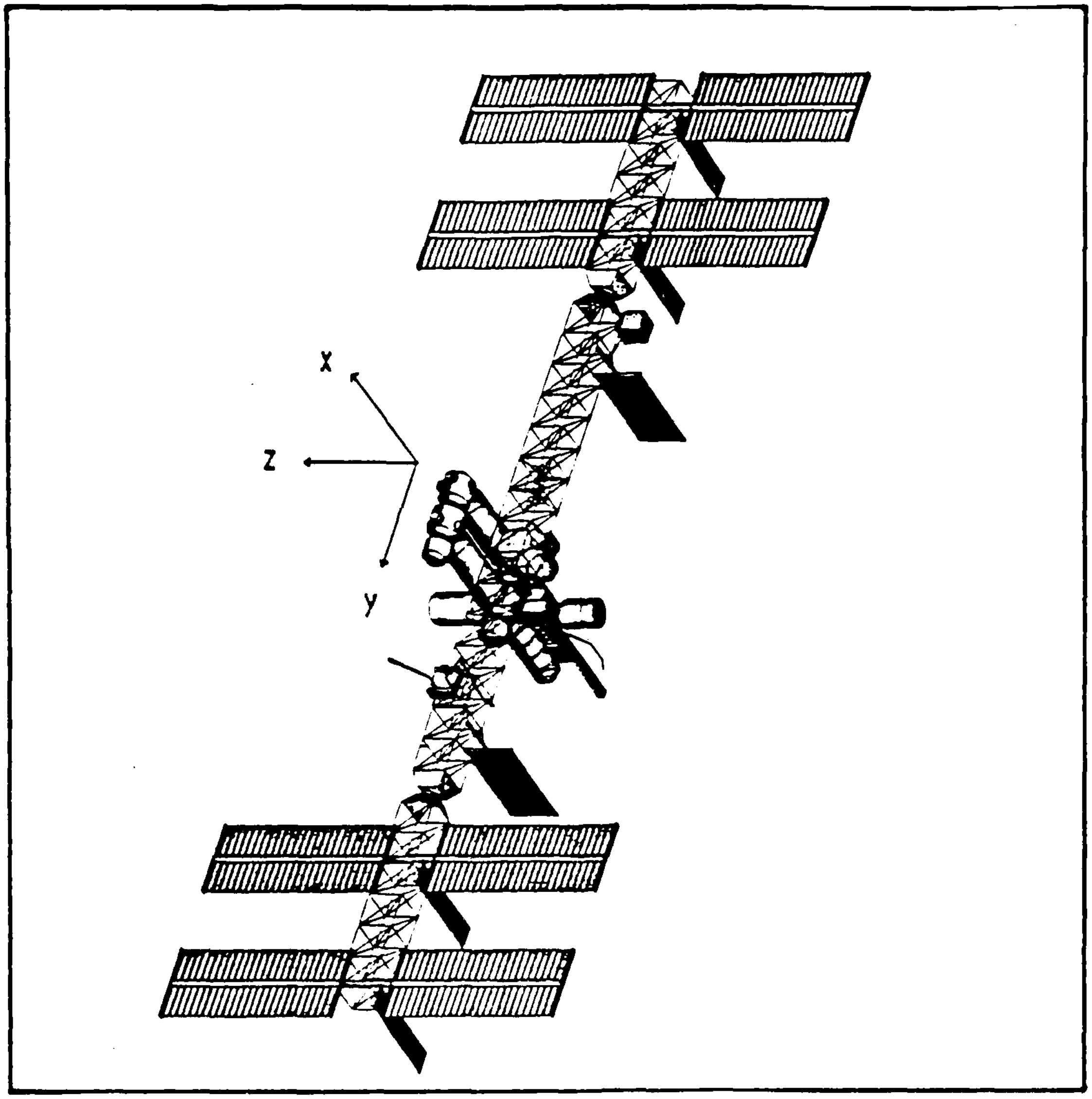


Fig. 3. Space Station Coordinate System (17:19,23)

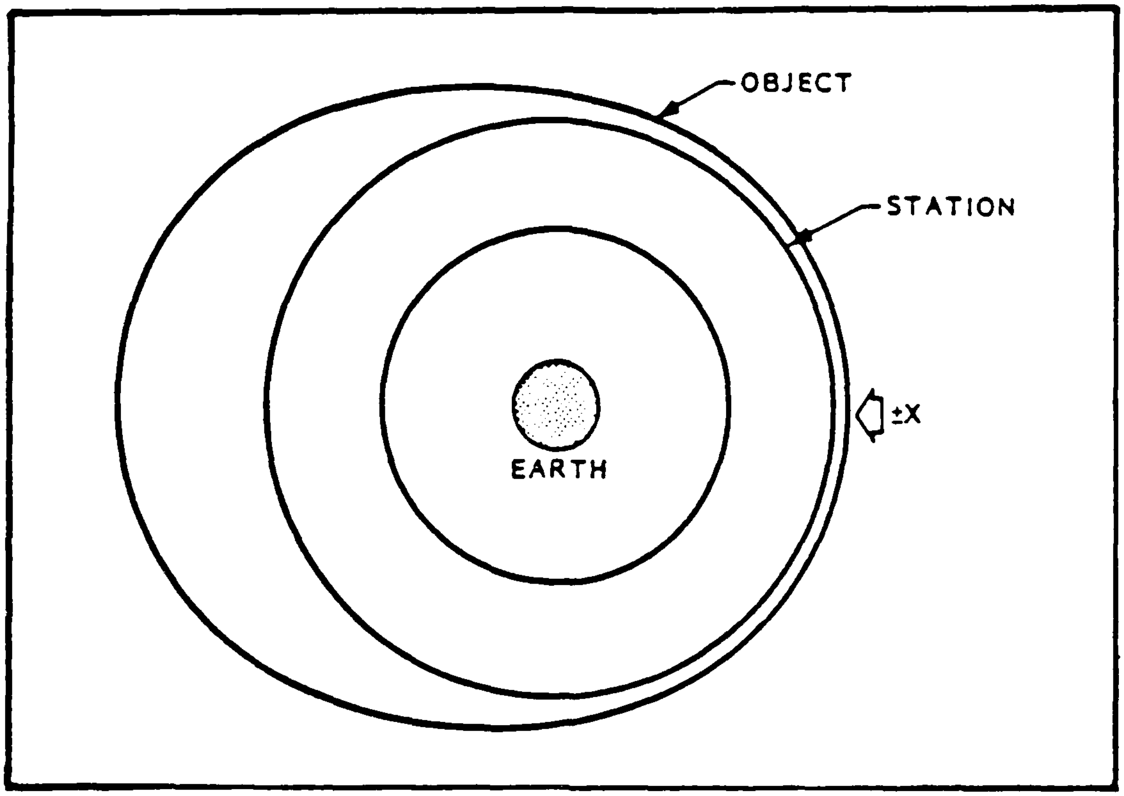


Fig. 4. X-Axis Trajectory (25:3)

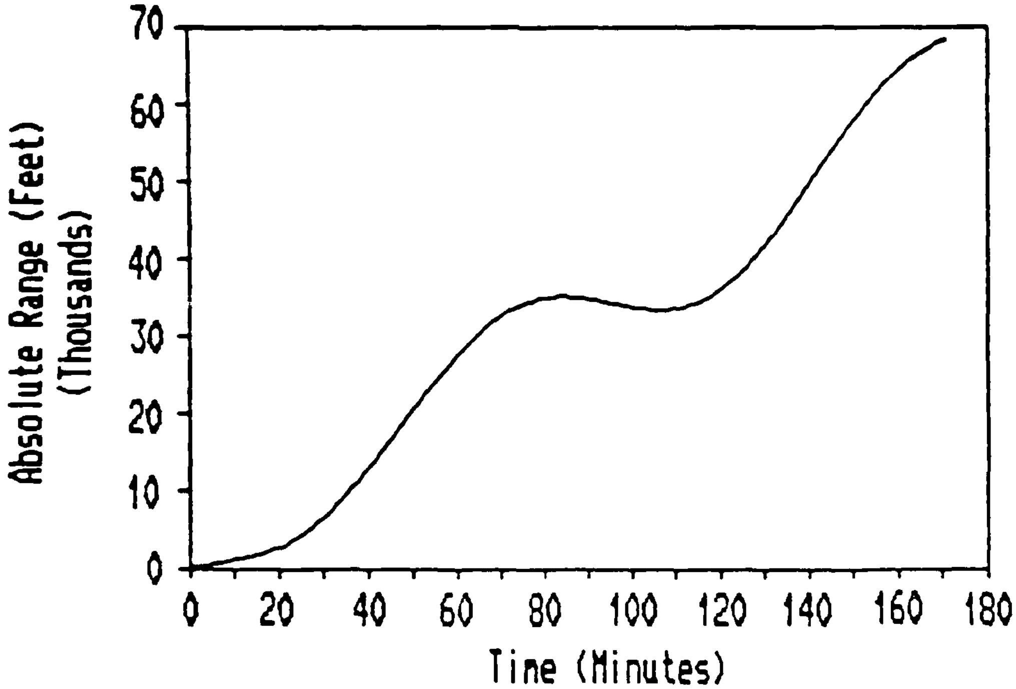


Fig. 5. X Axis Orbital Mechanics Effects,
Absolute Range, +x = 2 ft/sec (25:4)

A similar analysis is done for an object within an initial velocity of 2 ft/sec in the pure y-axis direction from the space station. The orbital mechanics of this situation describe a plane change (Figure 6). The interesting aspect of this purely y-axis direction is that the orbits of the object and space station cross paths twice each revolution. Figure 7 plots the absolute range between the object and space station. The maximum range in this case is 1,820 ft (25:6).

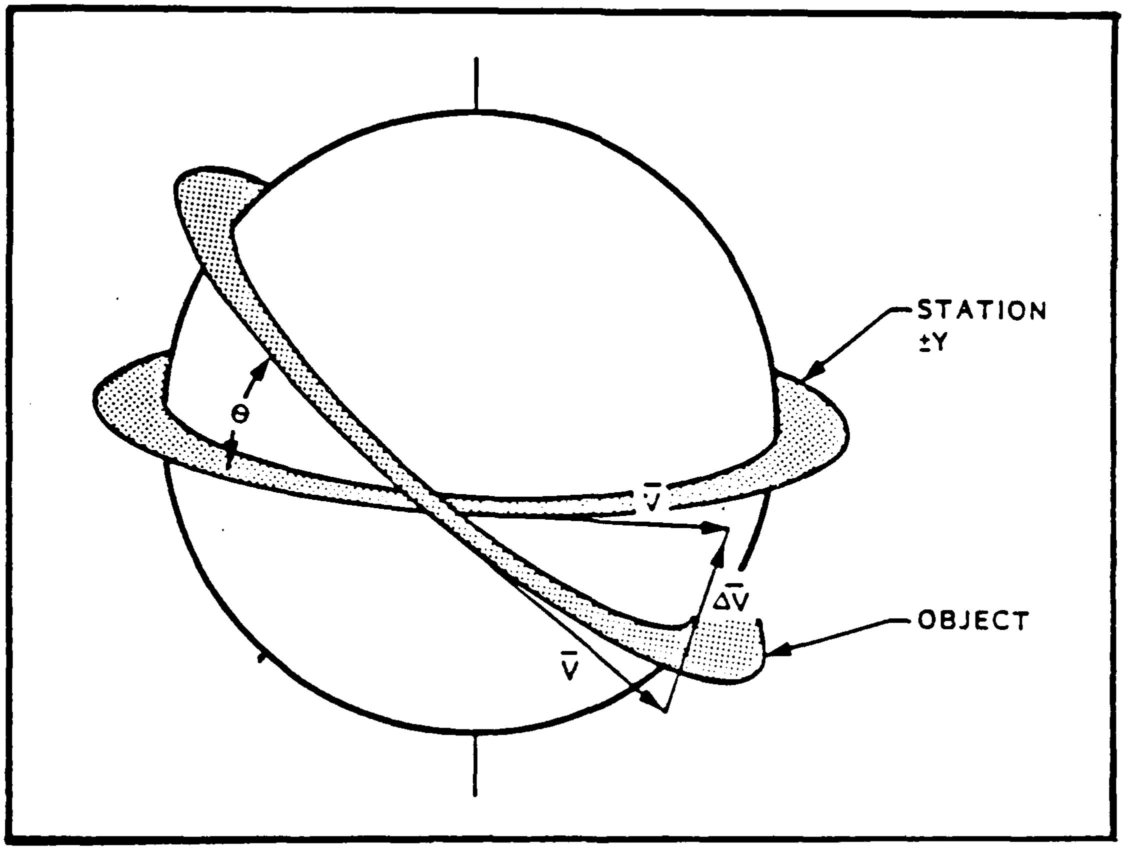


Fig. 6. Y-Axis Trajectory (25:5)

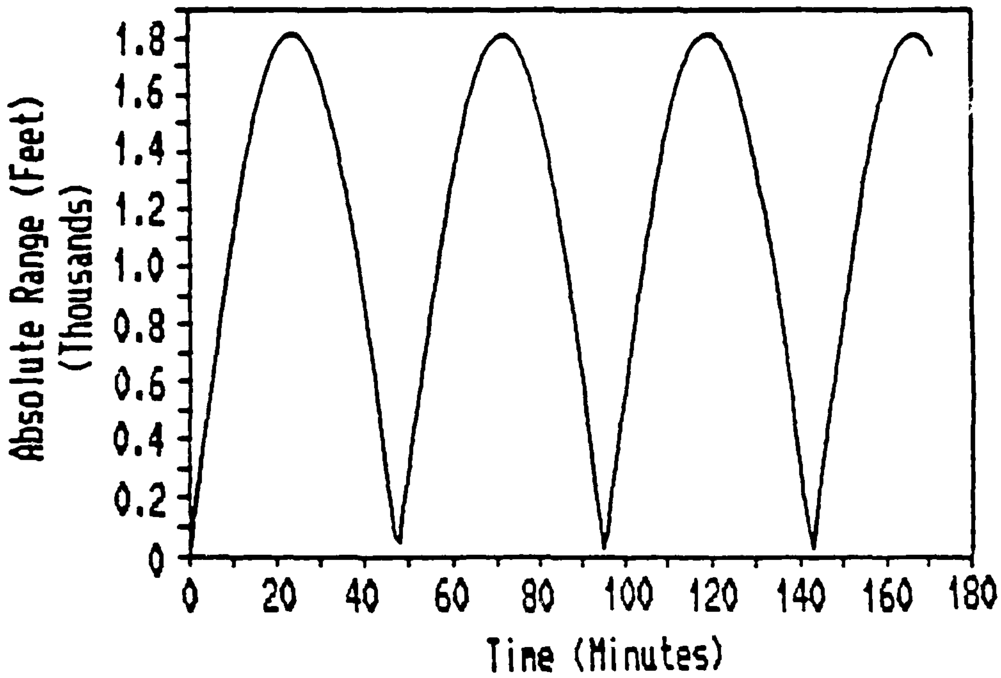


Fig. 7. Y-Axis Orbital Mechanics Effects
Absolute Range, +y = 2 ft/sec (25:6)

The analysis is also done on a purely z-axis basis. Again, the initial velocity is 2 ft/sec. In this case, the object and space station cross paths once an orbit (Figure 8). The absolute range is found in Figure 9 and has a maximum value of 7,200 ft (1.36 miles) (25:8).

This analysis shows the complexities of the orbital mechanics for the problems of EVA crew rescue and equipment recovery. These complexities are especially true if one considers that an object separating from the space station will most likely have velocity components in all three axial directions and thus have an extremely complicated orbit with respect to the space station. This analysis also shows that

a separation with an x-axis component can result in the object moving quickly away from the space station. One of the conclusions of this analysis is that the orbital mechanics become more complex as the object moves farther away from the space station. Therefore, the quicker the response to an object departing from the space station, the easier the rescue/recovery operation will be (36). Because of these complexities, each separation must be looked at on a case-by-case basis. With this technical background complete, the problem can now be defined.

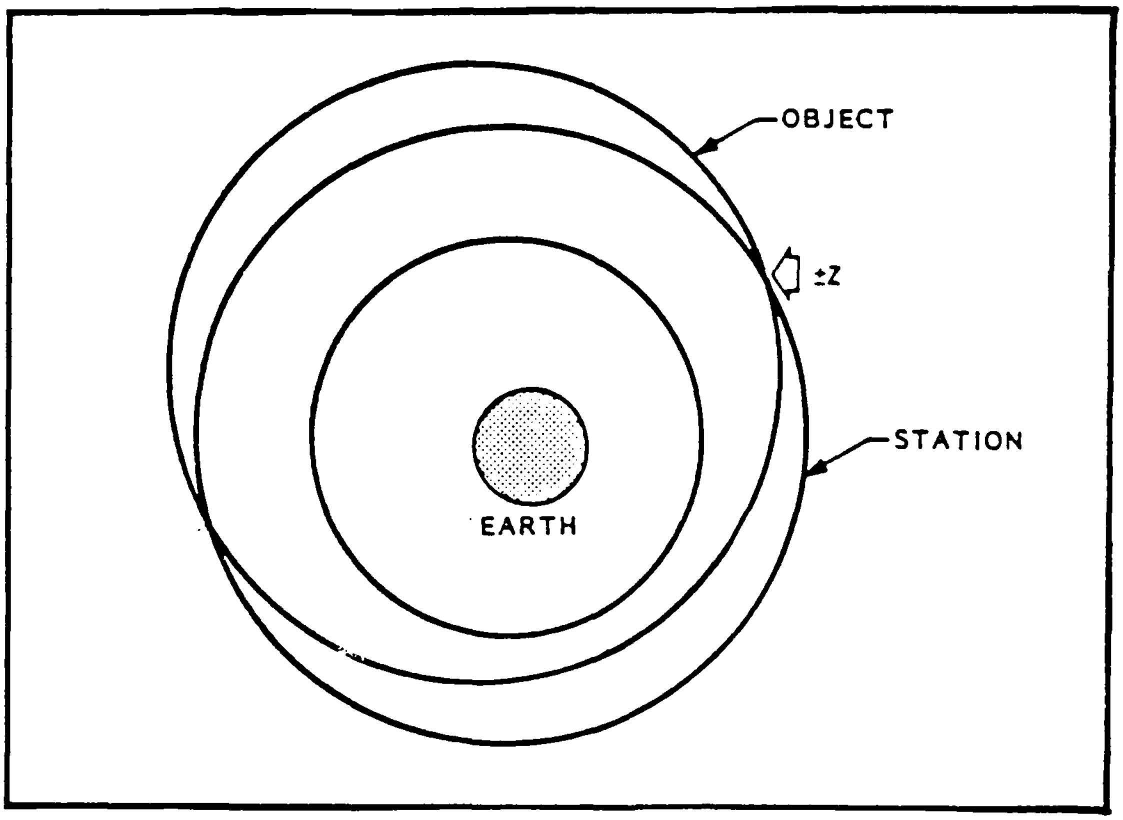


Fig. 8. Z-Axis Trajectory (25:7)

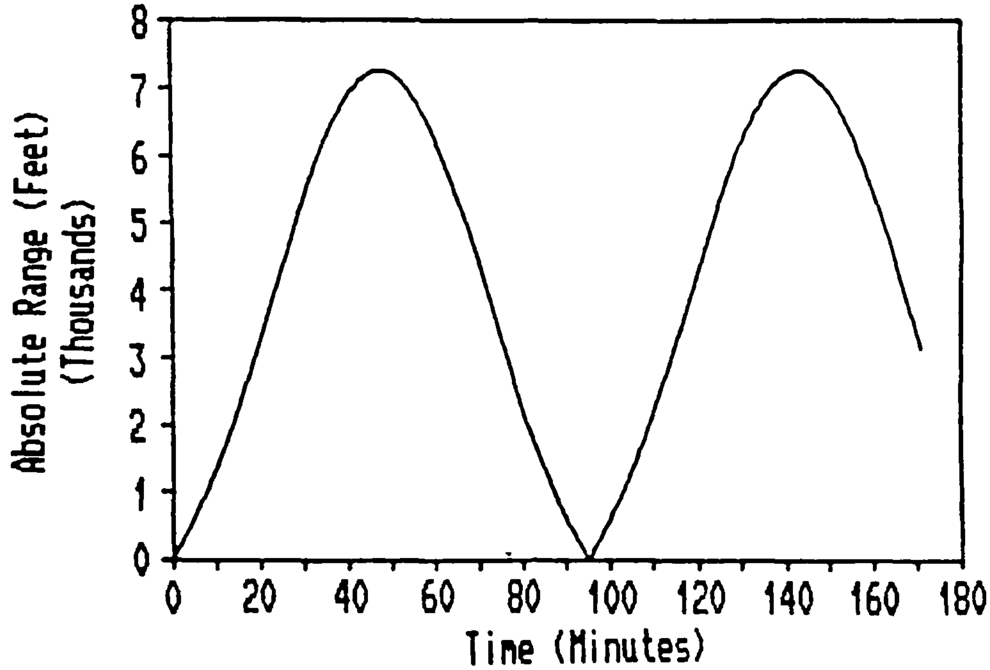


Fig. 9. Z-Axis Orbital Mechanics Effects
Absolute Range, +z = 2 ft/sec (25:8)

Concept Map

The approach taken to define these problems was concept mapping. Specifically, with the help of the NASA Space Station Office at Johnson Space Center (JSC), ten knowledgeable persons were interviewed independently and concept maps of their views on the problems of EVA crew rescue and equipment recovery were obtained. These knowledgeable persons included project managers, program engineers, and astronauts, all of whom had experience with either EVA or space rescue systems. Individual concept maps were generated during a three day visit to JSC. These individual concept maps were combined to form a consolidated concept map of the problems.

One of the concerns during the generation of the individual concept maps was that of the inability to focus on the problem. To this end, an initial (pre-concept map) survey was conducted to help attain this focus (see Appendix A). Once this focus was achieved, the interview for the concept mapping began.

These interviews proved to be of great value in defining the problems. The individual concept maps had some overlap among them (which was expected), but they also tended to center on the area the knowledgeable person felt most comfortable with. This indirectly allowed for the generation of a consolidated concept map which encompasses the entire realm of the problems.

The consolidated concept map for the problems of EVA crew rescue and recovery of equipment detached and adrift from the space station is found in Figure 10a, 10b, and 10c. In the generation of this map, the problems were broken down into the three sections. This breakdown occurred more by chance than by actually being planned. But the breakdown does fit extremely well into the Hall morphology and shows the flexibility of concept maps.

Several important observations need to be made with respect to these concept maps. First of all, this concept map is a consolidation of ten individual concept maps. As such, similar individual ideas were consolidated. Some of these individual ideas went into greater detail than is found

PROBLEM DEFINITION

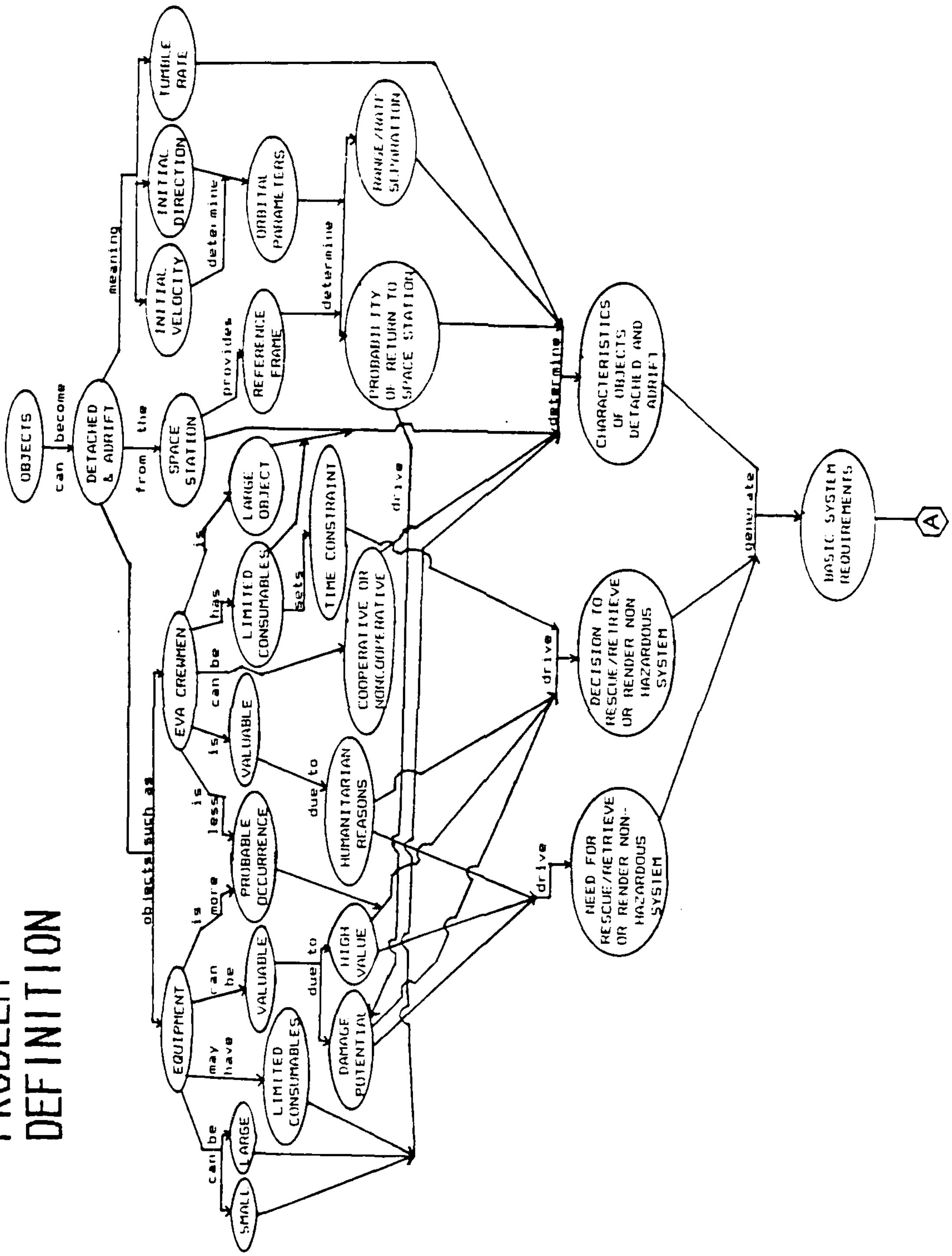


Fig. 10a. Consolidated Concept Map (Problem Definition)

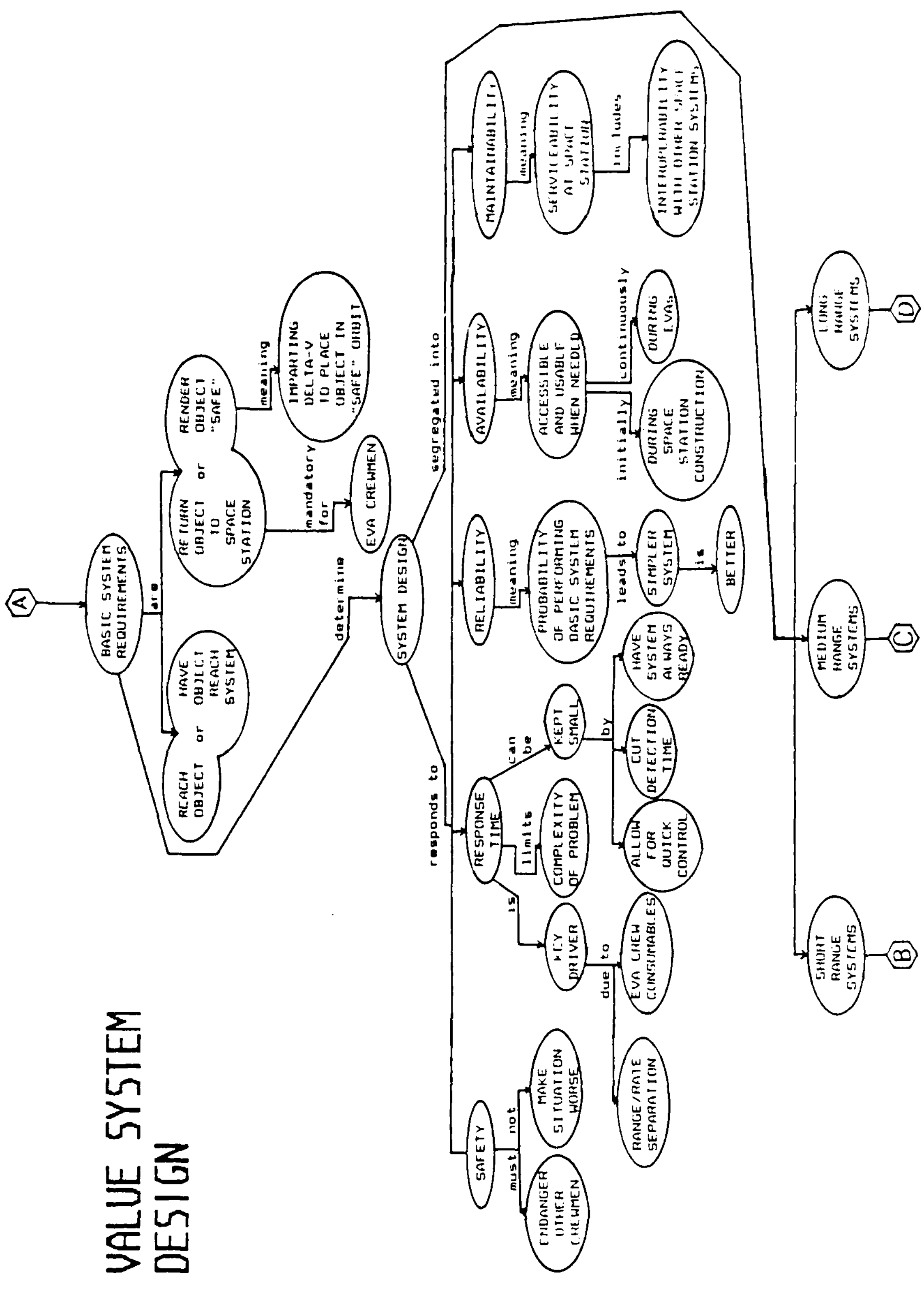


Fig. 10b. Consolidated Concept Map (Value System Design)

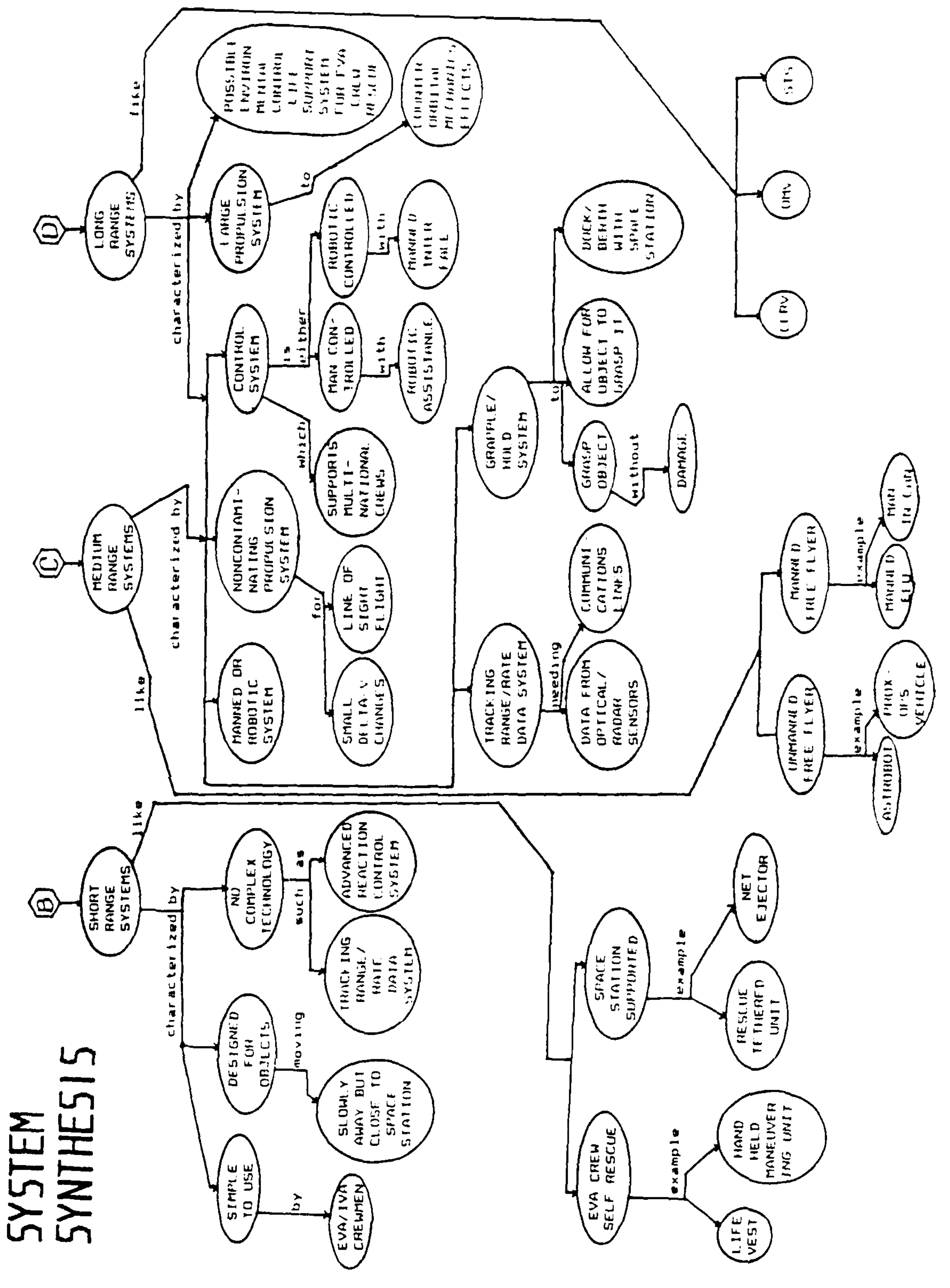


Fig. 10c. Consolidated Concept Map (System Synthesis)

in the consolidated concept map, but they are all represented. Secondly, the consolidation of the individual concept maps was done by the author. Hopefully, no biases were introduced into the consolidated version. The elimination of any biases is a reason why this consolidated concept map should be used as the starting point for a subsequent iterative analysis to the problems. The final observation about the consolidated concept map is its power to represent the problems. The ability to link several separate ideas to one central idea and easily display this linkage proved to be of enormous value in understanding the problems. The consolidated concept map shows all the factors and relationships which affect the problems. However, some of these factors need to be highlighted.

The problem definition section of the consolidated concept map (Figure 10a) shows several differences between equipment recovery and EVA crewmen rescue. First, when the separated object is an EVA crewmember, a definite time limit for rescue is established due to consumables. This may not be the case for detached equipment. Second, a separated EVA crewmember is a rather large object. This means that he/she is easier to track than a small object, like a nut, would be. Third, it was felt that certain adrift objects could present a hazard to the space station, but might not be worth the effort to recover or could best be recovered at a later time (3). This option would not exist for crew rescue.

Additionally, this decision area points out the scenario dependance of problems. The type of object adrift, the object's orbital characteristics, and the object's probability of returning to the space station all determine if the object will be rescued, recovered, or rendered non-hazardous. These object characteristics are all scenario dependent.

The consolidation of the individual concept maps pointed out that these are basic system requirements which all solution systems must meet. There are two basic system requirements for solution systems to the problems (Figure 10b). First, the solution system must get to the adrift object (EVA crewmember or equipment). This can be done by either having the system move to the object (as a free flying system would) or having the object move to the system (as in the case of a safety net). The second basic requirement is to either return the object to the space station or to place it in a safe orbit (a safe orbit is one with zero probability of the object hitting the space station). A third basic requirement, which is not specifically stated in the concept map, but rather implied, is that the solution system must operate over a range of distances from the space station. The solution system must be able to recover objects that are both near (within 100 ft) or far (distances where orbital mechanics play an important role). With these basic system requirements identified, several factors which determine the

systems design can now be identified. The consolidated concept map identified five system design factors. These factors are safety, response time, reliability, availability, and maintainability. These factors form the criteria on which the various solution systems will be evaluated.

It is interesting to note that since the problem is in the project planning and preliminary design phase of the project's life cycle, the knowledgeable persons at NASA did not feel that cost was an important criterion. Apparently, this factor becomes more important as the solution systems become better defined. This appears to be based on the premise that the ideal solution system will be the least expensive solution from a list of systems which all meet the problem's basic system requirements. The generation of this list of possible solution systems is also seen in the concept map.

Numerous solution systems to the problems were identified in the individual concept maps. The system synthesis section of the consolidated concept map (Figure 10c) shows the characteristics of these systems and provides some examples. The breakdown of the solution systems into short range, medium range and, long range is done to indicate that the range a solution system needs to operate within will determine the characteristics of that system. Because the range an object is away from the space station is scenario dependent, the choice of which type of solution system to use

is also scenario dependent. A short range system could not be used to recover an object which is at a long range. Likewise, a long range system may not be practical for the short range recovery of an object. Thus, range is another factor which impacts the complexity of the problems.

Summary.

The problems of EVA crew rescue and recovery of detached and adrift equipment from the space station are complex. The technical backgrounds on the Extravehicular Mobility Unit and the orbital mechanics of objects separating from the space station help explain some of the key complexities of the problems. The consolidated concept map defines the problems, shows the key areas of the problems, and ties these areas together. With this understanding of the problems, the analysis was initiated.

IV. Analysis

The purpose of the analysis section of this thesis was to provide direction as to which generic solution systems appear best suited to solve the problems of EVA crew rescue and equipment recovery. The analysis also evaluated the NASA provided contractor proposed solution systems to the problems. To this end, a review of the definition of a system is in order.

According to Athey, "systems are any set of components which could be seen as working together for the overall objective of the whole." (1:12) Thus, systems can be considered as groups of subsystems which work together to perform a common mission. In the case of this thesis, the common mission is to rescue EVA crewmembers and to recover detached and adrift equipment from the space station. The consolidated concept map established the environment within which the system must operate. It also established the criteria by which the systems were evaluated.

Evaluation Criteria

The evaluation criteria for this analysis are all found in the Value System Design section of the consolidated concept map (Figure 10b). This map not only lists the evaluation criteria, but also defines them. The first evaluation criterion is safety. Safety is defined as being

the freedom the rescue/recovery system provides from making the situation worse or from endangering other crewmembers. For example, a system could be considered safe if it has a 95% chance of not making the situation worse. The second evaluation criterion is response time. This criterion is defined as being the time it takes for the rescue/recovery system to detect the separation of an object and begin the physical process of returning the object or placing it in a safe orbit. Reliability is the third evaluation criterion and it is defined as the probability that the rescue/recovery system will successfully perform it's basic function of reaching the object (or having the object reach it) and returning the object to the space station (or placing it in a safe orbit). This criterion is a measurement of the probability of success for the rescue/recovery system and takes into account such factors as the probability that the system will not mechanically fail and the probability that the system was designed to meet the physical challenges of the rescue/recovery. The fourth evaluation criterion is that of availability. This criterion is a measurement of the systems accessibility and it's being usable when needed. For example, if the system is required to be available 90% of the time, then it can be "down" for repair the remaining 10% of the time. The trick is to insure that the rescue/recovery system is not "down" when it is needed. The final evaluation criterion is that of maintainability. This criterion

measures the serviceability of the rescue/recovery system. It is traditionally measured by the time it takes to repair or service the system. A brief summary of the evaluation criteria is found in Table I. With the identification of these criteria complete, they can now be applied using the Analytic Hierarchy Process.

TABLE I

EVALUATION CRITERIA AND DEFINITIONS

Evaluation Criterion	Definitions
Safety	Freedom from making the situation worse or from endangering other crewmembers
Response Time	The time from object separation to that of beginning the physical process of rescue/recovery, or render "safe"
Reliability	Probability that the rescue/recovery system will successfully perform its' basic functions of reaching the object (or have the object reach it) and return the object (or render "safe")
Availability	A probabilistic measurement of the percent of time the system will be accessible and usable during EVA periods
Maintainability	A measurement of the serviceability of the system. The time to repair or service.

Analytic Hierarchy Process (AHP) Analysis

As previously stated, AHP was used in the systems analysis phase of this thesis. To this end, the principles of AHP were also applied. The principle of decomposition, which calls for the breaking down of the problem into a hierarchical structure, was applied first. This was followed by the application of the principles of comparative judgement and of synthesis.

Principle of Decomposition. The AHP technique which takes a complex problem and breaks it down into simple parts is known as the principle of decomposition. This technique calls for the construction of a hierarchical structure "to capture the basic elements of the problem" (33:141). The principle calls for the breakdown of the problem into levels and sublevels. The levels contain the criteria upon which the subsequent sublevels are judged. In this thesis, the problems of EVA crew rescue and recovery of detached and adrift equipment were examined in a single hierarchical structure. This structure was derived from the consolidated concept map and is found in Figure 11.

The overall goal for the problem is located at the top of the hierarchy. In this case, it is simply to define the best system to solve the problems of EVA crew rescue and equipment recovery. The second level is that of the criteria to be used to judge the proposed systems. These evaluation criteria are the same ones identified in the consolidated

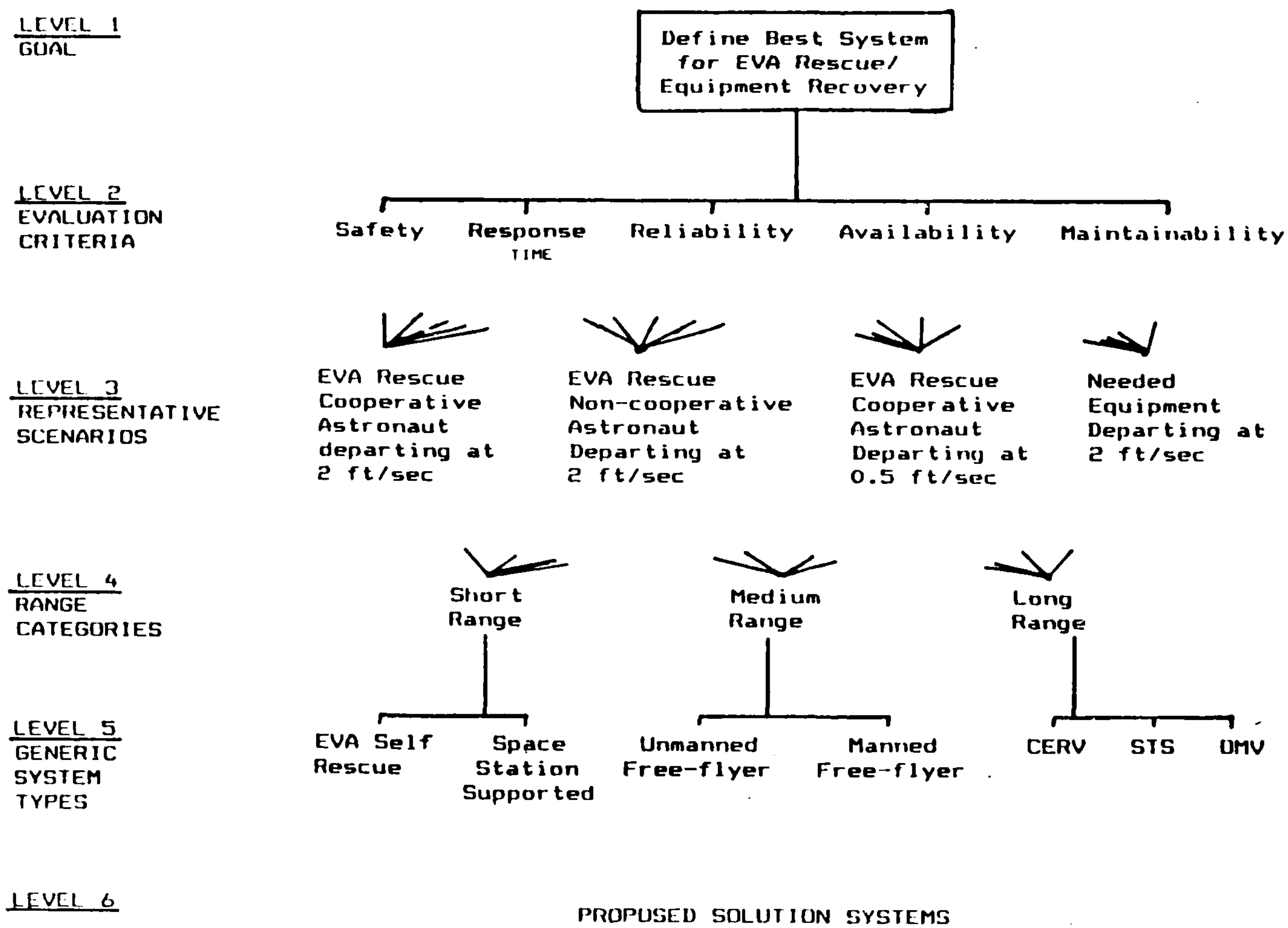


Fig. 11. AHP Hierarchy

concept map. The third level begins the process of breaking the alternatives down into manageable parts. This level defines four representative rescue/recovery scenarios within which the rescue/recovery system must operate and meet the evaluation criteria. The purpose of this level is to determine if there is scenario dependence on the solution systems. This breakdown is based on the assumption, which was verified in comments to the consolidated concept map, that the evaluation criteria are scenario independent. The fourth level breaks the alternatives into their respective range categories. The fifth level then breaks these range categories into generic system types. This breakdown is due to the vast number of contractor proposed solution systems provided by NASA. There is a sixth level to this hierarchy, but it is not expanded upon. Rather it is indicated by the term "Proposed Solution Systems." This sixth level is the list of the proposed solution systems. It is a list of both contractor and author generated solution systems and is found in Table II.

TABLE II

PROPOSED SOLUTION SYSTEMS

Generic System Types	Proposed Solution Systems
EVA Self Rescue	Hand Held Propulsive Devise Portable Aerosol Jet Safety throw line/rescue line Telescope Pole Hook

TABLE II (continued)

	EMU with Jetpack
Space Station Supported	Safety Nets/EVA Net Enclosure Redundant tethers/double tethers Boom extender Mobile Remote Manipulator System (MRMS) Smart end effector for MRMS Net ejector system Rescue Tethered Unit/Guided Tether Enclosed cherry picker Open cherry picker Shepherds Hook/Recovery Net Rescue Line/Life Ring
Unmanned Free-Flyer	Telerobotic vehicle Guided tether EVA Retriever Generic Space Robot Astrobot plus EEU Prox-Ops-Vehicle Free-flying independently directed excursion unit
Manned Free-flyers	Manned Maneuvering Unit (MMU) Extravehicular Excursion Unit (EEU) Homing unit plus EEU Man-in-can Manned Rover
STS	Space Transportation System (Space Shuttle)
OMV	Orbital Maneuvering Vehicle
CERV (Crew Emergency Return Vehicle)	Discoverer Gemini Lifting Body Vehicles AFE MOSES 6 Man Apollo LaRC Configuration

As can be seen in Table II, there are numerous contractor proposed solution systems to the problems. This analysis used AHP to point out the general directions the rescue/recovery system should take. The analysis was therefore only be carried out to the fifth level of the hierarchy structure. With this hierarchical structure complete, the AHP principle of comparative judgments was next applied.

Principle of Comparative Judgments. AHP uses a technique of comparative judgments to measure the relative importance of the evaluation criteria to the goal. These judgments are accomplished on a pairwise basis and are used to generate a weighting function for the evaluation criteria with respect to the goal. This function indicates the relative importance of each of the evaluation criteria.

In this thesis, the generation of the weighting function was accomplished by surveying the ten knowledgeable persons who were interviewed during the generation of the consolidated concept map. This survey follows the procedures outlined by Saaty and is found in Appendix B of this thesis. The results of the survey are found in Appendix C and the pairwise comparison matrix for the evaluation criteria is found below in Table III.

TABLE III

PAIRWISE COMPARISON MATRIX FOR THE EVALUATION CRITERIA

Criterion A	Criterion B S	RT	R	A	M
Safety (S)	1.000	3.00	1.56	2.46	5.19
Response Time (RT)	0.333	1.00	0.67	0.85	2.42
Reliability (R)	0.641	1.49	1.00	1.93	4.88
Availability (A)	0.406	1.18	0.518	1.00	4.21
Maintainability (M)	0.193	0.413	0.205	0.237	1.00

This matrix is read row by column and shows the relative importance of one of the evaluation criterion to another. For example, Safety (S) (criterion A) has a relative importance of "3.00" to the criterion Response Time (RT) (criterion B). The scale used in this matrix is listed below and would have a reading of "3" meaning that of weak importance. Thus in this example, the criterion of Safety is weakly more important than the criterion of Response Time. These matrix weights were generated by taking the geometric mean of the survey results (see Appendix C).

TABLE IV

MATRIX WEIGHTING FACTORS

FACTOR	MEANING
0.2	Criterion A is strongly less important than criterion B
0.33	Criterion A is weakly less important than criterion B
1	Criterion A is of equal importance to criterion B
3	Criterion A is weakly more important than criterion B
5	Criterion A is strongly more important than criterion B
All other values	Intermediate values

From the comparison matrix, geometric means were calculated and normalized to generate the overall weights for the evaluation criteria. These overall weights are found in Table V.

TABLE V

OVERALL EVALUATION CRITERIA WEIGHTS

Evaluation Criterion	Weight
Safety	0.377
Response Time	0.142
Reliability	0.257
Availability	0.168
Maintainability	0.055

These overall weights indicate how much each of the evaluation criteria contribute to the overall goal of the AHP Hierarchy, and form the weighting function. The weighting function for this analysis is therefore:

System Rating = 0.337(Safety factor) + 0.142(Response time) + 0.257(Reliability factor) + 0.168(Availability factor) + 0.055(Maintainability factor)

These weights are all based on the survey results. AHP has a procedure which checks the comparisons made in the survey to indicate if the judgments made by the knowledgeable persons were consistent. This procedure generates a measurement called a consistency ratio which is a measurement

of how this survey judgments relate to random judgments. The results of this survey have a consistency ratio of 0.01 which is well within the minimum standard set by Saaty (below 0.1) (33:142,143). Therefore, the judgments and calculated weights are consistent. With the weighting function set, the rest of the analysis proceeded.

The next step of the analysis was to evaluate the various scenarios and associated generic system types to gain insight into the direction to take with the respect to the evaluation criteria. Thus, each of the various generic system types were compared to the other generic system types within their own range category in the light of the evaluation criteria and scenario. For example, one of the comparisons was stated as "which short range generic solution type is preferred as being the safest for the scenario of a cooperative astronaut becoming detached and adrift from the space station departing at a initial velocity of 2ft/sec, is it the EVA Self Rescue or Space Station supported generic solution type?" Following this preference choice, a weight factor is assigned which indicates the strength of that preference. The scale used here is the same as used in Appendix B. These preferences are then examined on a scenario basis to see if any overall direction can be determined. The definitions of the scenarios, range categories, and generic system types are all found in Table VI below.

TABLE VI

DEFINITIONS

Level	Definition
Level 3: Representative Scenarios	
1) EVA Rescue, Cooperative departing at 2ft/sec	An EVA crewmember becomes separated from the Space Station. He/She is separating at a rate of 2ft/sec and is cooperative.
2) EVA Rescue, Non-cooperative departing at 2ft/sec	An EVA crewmember becomes separated from the Space Station. He/She is departing at a rate of 2ft/sec and is non-cooperative (unconscious).
3) EVA Rescue, Cooperative departing at 0.5ft/sec	An EVA crewmember becomes separated from the Space Station. He/She is separating at a rate of 0.5ft/sec and is cooperative.
4) Needed Equipment departing at 2ft/sec	A piece of equipment has been determined to require recovery. It is departing at a rate of 2ft/sec.
Level 4: Range Categories	
1) Short Range	This is the area within 100 ft of space station.
2) Medium Range	This is the area outside the short range limit where orbital mechanics are not a major consideration for rescue/recovery. Maneuvering within this range can be done through line of sight flights.

TABLE VI (continued)

	This area has been generally defined as the Space Station Proximity Operations Zone (roughly a sphere of 1 kilometer around the space station) (3).
3) Long Range	This is the area outside the medium range where Orbital Mechanics must be considered in a rescue/ recovery.
Level 5: Generic System Types	
1) EVA Self Rescue	These system types call for the separated EVA crewman to perform self rescue within short range of the space station. Example systems include hand held maneuvering unit and safety line.
2) Space Station Supported	These system types call for rescue to be performed by someone other than the astronaut requiring rescue within short range of the space station. Example systems include extendible pole hook and net ejector system.
3) Unmanned Free-Flyers	This medium range system type calls for an unmanned free flying system to be used in rescue/recovery. Example systems include Generic Space Robot and Astrobot.
4) Manned Free-Flyers	This medium range system type calls for a manned free flying system to be used in rescue/recovery.

TABLE VI (continued)

	Example system includes the Manned Maneuvering Unit (MMU).
5) CERV	This long range system type is the Crew Emergency Return Vehicle. It is a system currently under development which will have the ability to safely return astronauts to earth if a problem occurs at the space station and the space shuttle is not available. This is a manned system.
6) STS	This is the space transportation system also known as the space shuttle to be used for long range rescue/recovery.
7) OMV	This is the Orbital Maneuvering Vehicle, a long range unmanned free flyers currently under development.

The evaluation of the scenarios and associated generic solution types was performed through telephone interviews with technical advisors from NASA (28;39). The results of these evaluations can best be seen during the application of the last principle of AHP: the synthesis of priorities principle.

Synthesis of Priorities. The synthesis of priorities calls for the evaluation of the hierarchy by using the

weighting function and preference measurements. This is the step where the results of the analysis take shape. In this thesis, these results indicate the direction the overall systems solution to the problems should take. The results of the analysis are best seen on the basis of the range categories and the associated generic system types. The interviews with the technical advisors from NASA indicated the directions to be taken within each of these range categories.

For the near range category, the indicated direction for the generic system type was found to be scenario dependant. The NASA technical advisors indicated that in scenarios where a cooperative astronaut had separated from the space station, an EVA self rescue generic system type was preferred. This preference is due primarily to the safety considerations with this type system. Additionally, for the scenario of equipment recovery or rescue of a noncooperative astronaut (unconscious), a space station supported generic system type was preferred. This choice was made due to the fact that the EVA self rescue generic system type is not applicable in these scenarios and thus a space station supported generic system is the only choice available. Therefore, two generic system types are preferred in the near range rescue/recovery situation. These systems are an EVA self rescue system for rescue of cooperative astronauts requiring rescue, and a space station supported system for rescue/recovery of

everything else. Scenario dependance was found only in the case of near range operations.

In the medium range category, the preferred generic system type was the Unmanned Free-Flyer. This system had overall preference in all the evaluation criteria except reliability to that of the Manned Free-Flyer. The manned free flyer had greater reliability due to the fact that it is currently flying and has been proven reliable (MMU). However, the other evaluation criteria, especially safety, all had an unmanned free-flyer as the preferred system.

The long range category proved to be the area where the real strength of AHP showed itself. Here, the Space Shuttle, Orbital Maneuvering Vehicle (OMV), and Crew Emergency Return Vehicle (CERV) were all compared. The comparisons showed that each vehicle had areas where it was preferred over the other vehicles. For example, it was felt by the NASA technical advisors, that the CERV was the most available of the vehicles. The calculated normalized geometric preference means for each vehicle by evaluation criteria are given in Table VII. These calculations show which generic system type is preferred for each evaluation criteria. Again, the preference ratings were scenario independent.

TABLE VII

LONG RANGE GENERIC SYSTEM TYPES
PREFERENCE RATINGS

Generic System Type	Evaluation Criteria S	RT	R	A	M
CERV	0.09	0.13	0.14	0.51	0.39
OMV	0.65	0.77	0.28	0.43	0.61
STS	0.26	0.10	0.58	0.06	0.10

NOTE: S=Safety, RT=Response Time, R=Reliability, A=Availability, M=Maintainability

These preference ratings were then used in the weighting function to generate an overall rating for each long range generic system type. This calculation was done by summing the product of the individual evaluation criteria weights and preference ratings for each generic system. For example, CERV had an overall rating of 0.1864 ((0.337*0.09) + (0.142*0.13) + (0.257*0.14) + (0.168*0.51) + (0.055*0.39) = 0.1864). The overall ratings for each long range generic system type indicated that the OMV was the preferred direction for a long range generic solution type. The overall ratings for each system are provided in Table VIII.

TABLE VIII

OVERALL RATINGS FOR LONG RANGE GENERIC SYSTEMS

System	Rating
CERV	0.1864
OMV	0.50564
STS	0.26646

Summary.

This analysis has provided the direction as to which generic system types appear best suited to solve the problems of EVA crew rescue and equipment recovery. It has shown that for a near range rescue/recovery, both an EVA Self Rescue and a Space Station supported type system are preferred. The analysis has shown that for a medium range rescue/recovery, an unmanned free flyer is the preferred system. For a long range rescue/recovery, the analysis has shown that the OMV is the preferred system. Thus, the directions to be investigated have been determined.

The next step in this analysis would be to form a comprehensive rescue/recovery system using elements of each of the generic system types. A comprehensive rescue/recovery system would therefore be made up of one of the proposed EVA Self Rescue systems, plus one of the proposed Space Station supported systems, plus one of the proposed unmanned free flyer system, and finally the OMV. These comprehensive rescue/recovery systems would then be examined in light of the evaluation criteria and an overall "best" rescue/recovery system would be determined. But, there are numerous systems which need to be examined. In fact, with the five EVA Self Rescue Systems, the eleven Space Station Supported Systems, the seven Unmanned Free-Flyer Systems and the OMV, there are 385 combinations of comprehensive rescue/recovery systems which can be generated. The evaluation of this large a

number of rescue/recovery systems is beyond the scope of this thesis. However, an examination of the various contractor proposed solutions is included in Appendix D.

V. Example Rescue/Recovery System

The analysis previously presented shows the direction to take in the rescue of EVA crewmembers and the recovery of detached and adrift equipment from the space station. The direction has been in the form of determining the preferred generic system type for each of the range categories. By combining these preferred generic system types, a comprehensive rescue/recovery system for the problems can be generated. If carefully constructed, this system will allow the individual generic system types to complement each other and provide an integrated systems approach to solving the problems of EVA crew rescue and equipment recovery. This section of the thesis will examine one such system to provide an example and to show the synergistic effects of this systems approach.

Basic Configuration.

The basic configuration of the example rescue/recovery system consists of four subsystems. These subsystems are the Extravehicular Mobility Unit (EMU) with jetpack, a shepherd's hook/recovery net subsystem, the EVA Retriever, and the Short Range Vehicle (SRV) module of the Orbital Maneuvering Vehicle. All these subsystems work together to rescue/recover objects which detach from the space station. The EMU with jetpack and the shepherd's hook/recovery net

subsystems are designed for short range operations. The EVA Retriever will work the medium range operations. The SRV will operate in the long range. However, all these subsystems are responsive in nature; they only operate when something has become detached from the space station. A responsive system, such as the one outlined above, has its' merits, but a responsive system is not the total answer to the problems of EVA crew rescue and equipment recovery. The rescue/recovery system must also have a preventive system which will limit the possibilities of objects becoming detached from the space station in the first place.

Such a preventive system is already in place on the space shuttle. It calls for the tethering of all objects (equipment and crewmen) at all times and requires that this emphasis on tethering be an important part of EVA crew training (37). Although history has shown that this preventive system will not eliminate the problems of equipment floating away, it is at least a step in recognizing the problem. Therefore, this preventive system will be assumed to be a part of the example rescue/recovery system for the space station. With the preventive system now in place, the responsive system can be examined.

Short Range Subsystem.

The responsive section of the example rescue/recovery system calls for two separate short range subsystems. These

systems are the EMU with jetpack subsystem for EVA self rescue and the shepherd's hook/recovery net subsystem for assisting with EVA rescue and for recovering adrift equipment. Both of these subsystems are designed to work a short distance from the space station (less than 100 ft) and to deal with objects which slowly float away from the space station.

<u>Extravehicular Mobility Unit (EMU) with Jetpack.</u> This EVA self rescue system is a basic EMU which has been modified to include a single flight mini-jetpack (see Figure 12). This jetpack, using a cold gas system (rechargeable), is designed as a small scale self-contained maneuvering unit. However, it is designed to accomplish the following on a single flight basis: 1) automatic attitude stabilization to stop EVA crewmember tumble, 2) directed pitch, yaw, and roll to orientate the astronaut towards the space station (voice activated command system), and 3) small thrustings of the system to direct the astronaut back to the space station. The amount of thrust (delta velocity) this system has is limited. The system should be designed to accomplish a self rescue for the scenario which is felt to be the most likely of all the EVA rescue scenarios. This scenario is that of a cooperative astronaut departing at a relatively slow rate (14). Therefore, this EVA self rescue subsystem is designed to accomplish a rescue for scenarios when the initial departing velocity is less than 2 ft/sec.

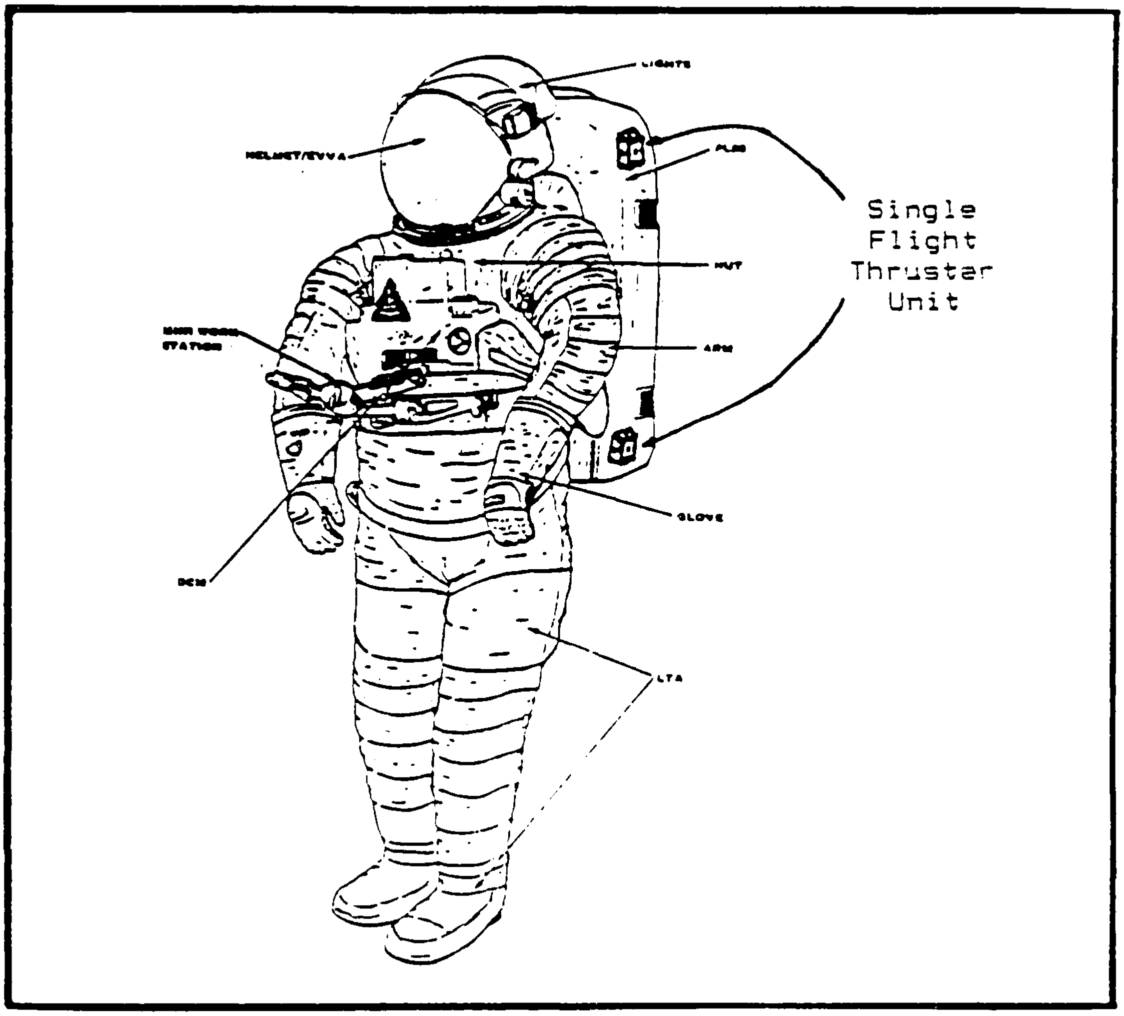


Fig. 12. EVA Self Rescue Subsystem
(EMU Picture (32:3);Single
Flight Thruster Unit (Author))

The advantages of this type of self rescue subsystem are that it is self contained, directly attached to the astronaut (allows for known center of mass), controllable by the drifting astronaut, and because it is designed for a single flight, relatively small in size. Additionally, such a self rescue subsystem could be activated by a drifting astronaut

anytime rescue is required (even when the initial departing velocity is greater than 2 ft/sec) to support the rescue attempts by the other subsystems of the rescue/recovery system. For example, if the departing velocity is greater than the subsystem's designed criteria, the activation of this self rescue subsystem would slow that initial departing velocity and stabilize the attitude of the astronaut requiring rescue. These actions would 'buy time' for the rescue by other subsystems of the overall rescue/recovery system. This action would increase the probability of successfully accomplishing the rescue.

The EMU with jetpack is an example of a subsystem which can be used for EVA crew rescue. However, this example rescue/recovery system also addresses the problem of equipment recovery. The short range subsystem for this mission is the Shepherds' Hook/Recovery Net.

Shepherds' Hook/Recovery Net. This subsystem is the space station supported subsystem of the rescue/recovery system. It is basically an extendable pole with a shepherds' hook on one side and a capture net on the other side (see Figure 13). This subsystem is designed to be manually operated by an EVA astronaut to either capture loose equipment or to assist in the rescue of another astronaut. The subsystem can either be manually extended, or extended through the use of a cold gas propulsion system located at

the head of the unit. The unit is restrained by tethers which are designed to allow the extended pole to slide within the restraints. This is done by attaching the tethers to a ring which encircles the pole and allows the pole to slide to a stop point. The shepherds' hook is designed to allow a drifting astronaut to grasp it or to encircle a noncooperative astronaut. The hook also serves as a mass offset for the recovery net section of the unit. The recovery net will capture floating objects through the use of an electrically activated door which closes the net around the object. This capture limits the possibilities of objects bouncing out of the net and departing in a new direction.

Because this space station supported subsystem is EVA crew operated, it could best be utilized if positioned in areas where EVA activity is planned. This will facilitate a quick reaction time for the subsystem. In fact, it may be wise to have several of these subsystems placed in strategic locations throughout the space station in order to increase the chances of successfully recovering objects which become loose. However, due to this subsystem's limited range, a medium range system must also be employed.

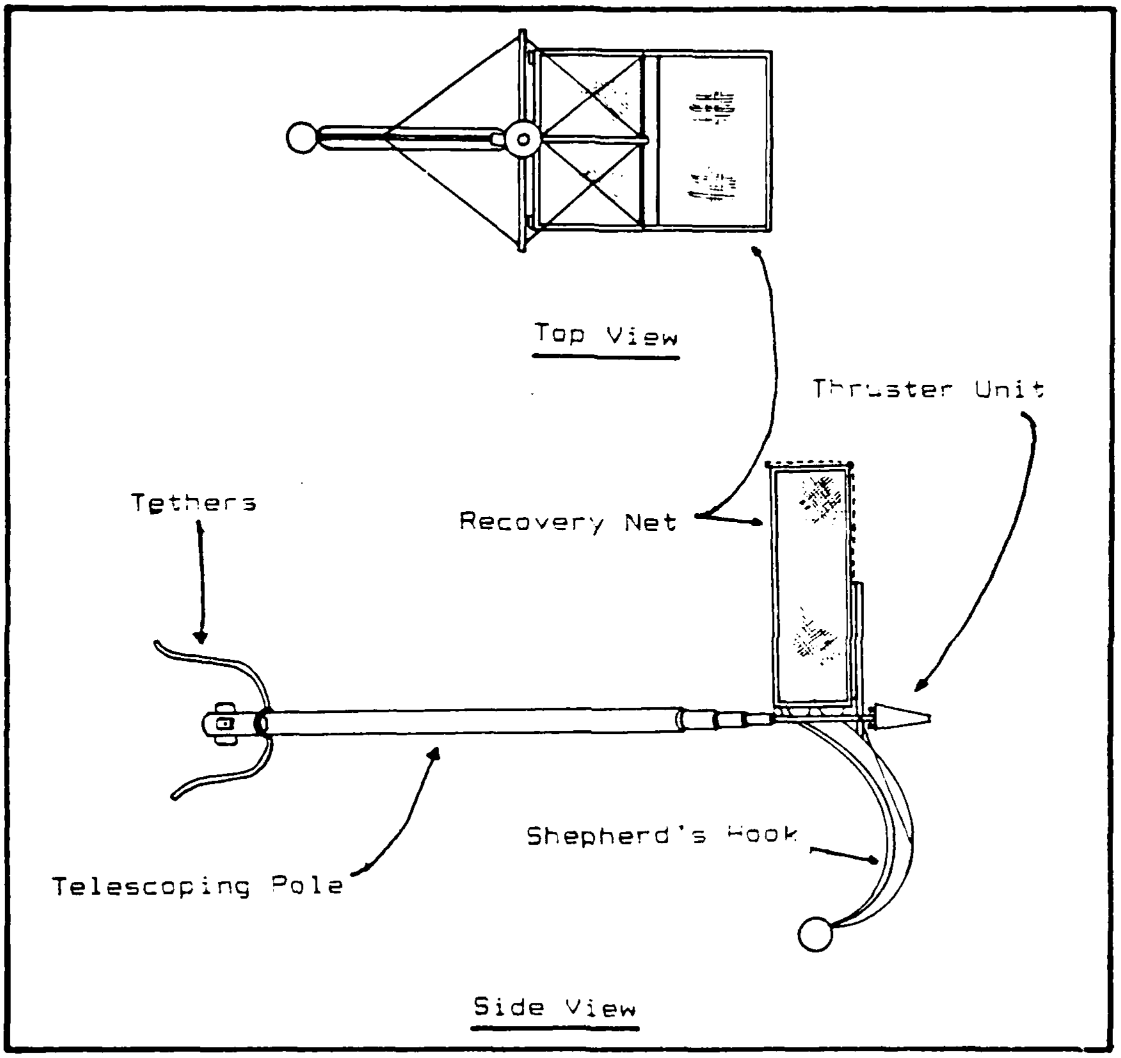


Fig. 13. Space Station Supported Subsystem

Medium Range Subsystem.

The medium range subsystem for the rescue/recovery system is the EVA Retriever with slight modifications. The EVA Retriever is a current NASA program which has been developed by Johnson Space Center to fulfill the space station's requirements for an EVA rescue system (22:5). This subsystem consists of a highly autonomous robot, complete with grappling devices which uses the Manned Maneuvering Unit (MMU) as a propulsion unit (Figure 14). Simulations done at the Martin Marietta Space Operations Simulator have shown that the MMU has the capability to perform rescue operations of adrift EVA crewmembers (31:11). The EVA Retriever extends this MMU capability into the robotics domain. As such, the EVA Retriever is controlled through a man-in-the-loop process, but has a built-in capacity to acquire and track drifting objects. A modification to this NASA program is the addition of a capture net (similar to the one on the shepherds' hook/recovery net subsystem) to be used to recover drifting equipment. This addition would make the subsystem more versatile. This versatility is also seen in it's concept of operations.

The concept of operations for the EVA Retriever calls for the unit to be on stand-by during all EVA operations. This allows for immediate response in the event of a rescue/recovery contingency (22:5). This concept of operations would be modified for the example rescue/recovery

system by calling for the immediate activation of the system in cases of EVA rescue and by having only selective activation in the cases of equipment requiring recovery. Immediate activation in the case of EVA rescue is required because of the value of human life, both in the humanitarian and political sense (3). This immediate activation would allow the EVA Retriever to serve as a back-up to the short range subsystems of the rescue/recovery system. If these short range subsystems fail to perform the rescue, the EVA Retriever would then be in a position to attempt the rescue. In the case of selective activation, the EVA Retriever would be deployed only in those cases where the equipment to be recovered is either of great value or departs on a trajectory which will cause it to impact with the space station. Additionally, this selective activation would only occur after the short range subsystems fail in their attempts at recovery. The back-up to the EVA Retriever is the long range subsystem of this example rescue/recovery system.

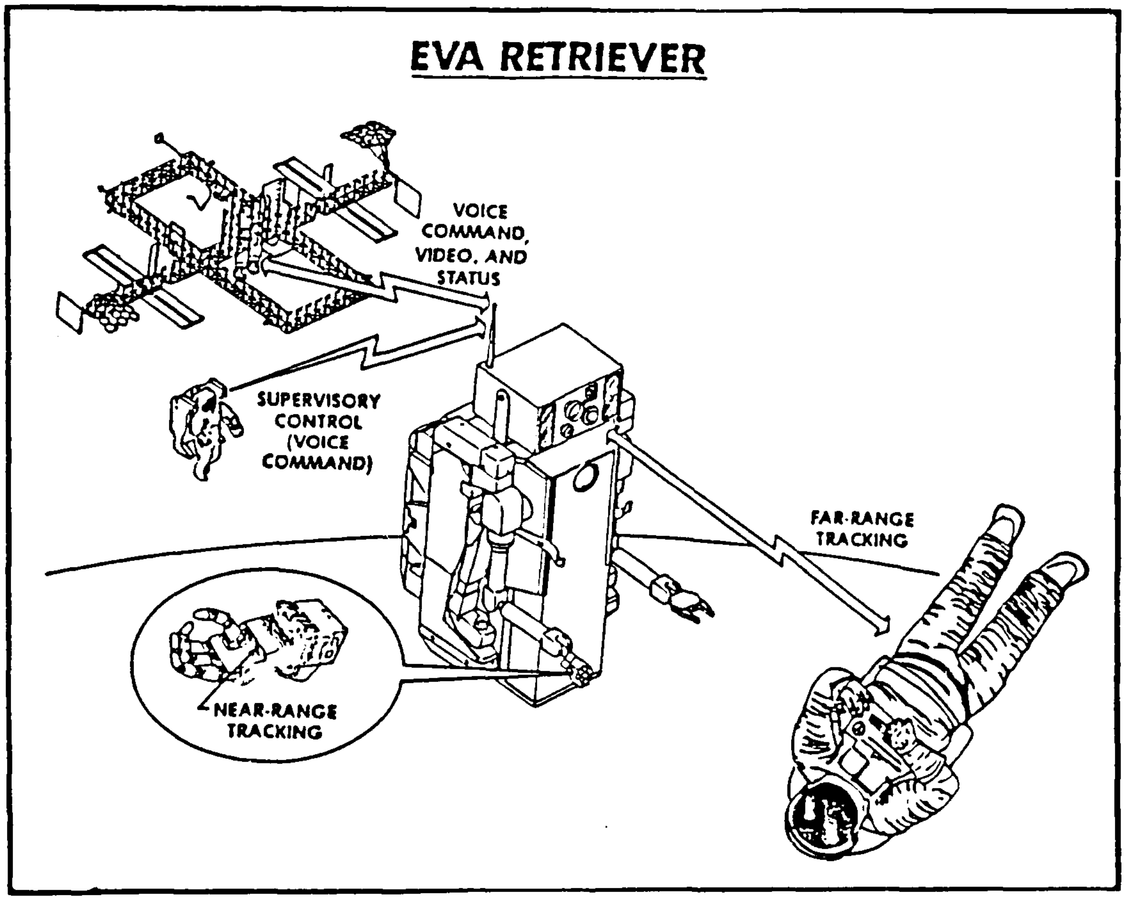


Fig. 14. Medium Range Subsystem (22:6)

Long Range Subsystem.

The long range subsystem of this example rescue/recovery system is the Orbital Maneuvering Vehicle (OMV). Specifically, the Short Range Vehicle (SRV) module of the OMV (see Figure 15). This module of the unmanned, reuseable, and remotely operated OMV is designed to place, rendezvous, retrieve, and berth payloads in space (27:4). The SRV with its two reaction control systems will have the potential of

up to a 700 ft/sec delta velocity change which can be used to capture a 1000lb object and return this object to the space station (27:6). This large potential delta velocity and the two reaction control systems (Hydrazine for large delta velocity changes and the non-contaminating cold gas system for close maneuvering) make this vehicle ideal for the rescue/recovery operations of objects detached from the space station. In fact, the ability of this vehicle to recover objects has had attention at Marshall Flight Center, where NASA is designing a modification kit to the SRV which is specifically designed to recover drifting orbital debris (27:9). Because of these capabilities, the SRV module of the OMV is the long range subsystem of this example rescue/recovery system.

The concept of operations for the SRV would very much follow the same lines as it was for the EVA Retriever. The SRV would be immediately activated for EVA crew rescue operations and would be selectively activated for equipment recovery operations. Again, this long range subsystem would serve as the back-up to the short and medium range subsystems of this example rescue/recovery system.

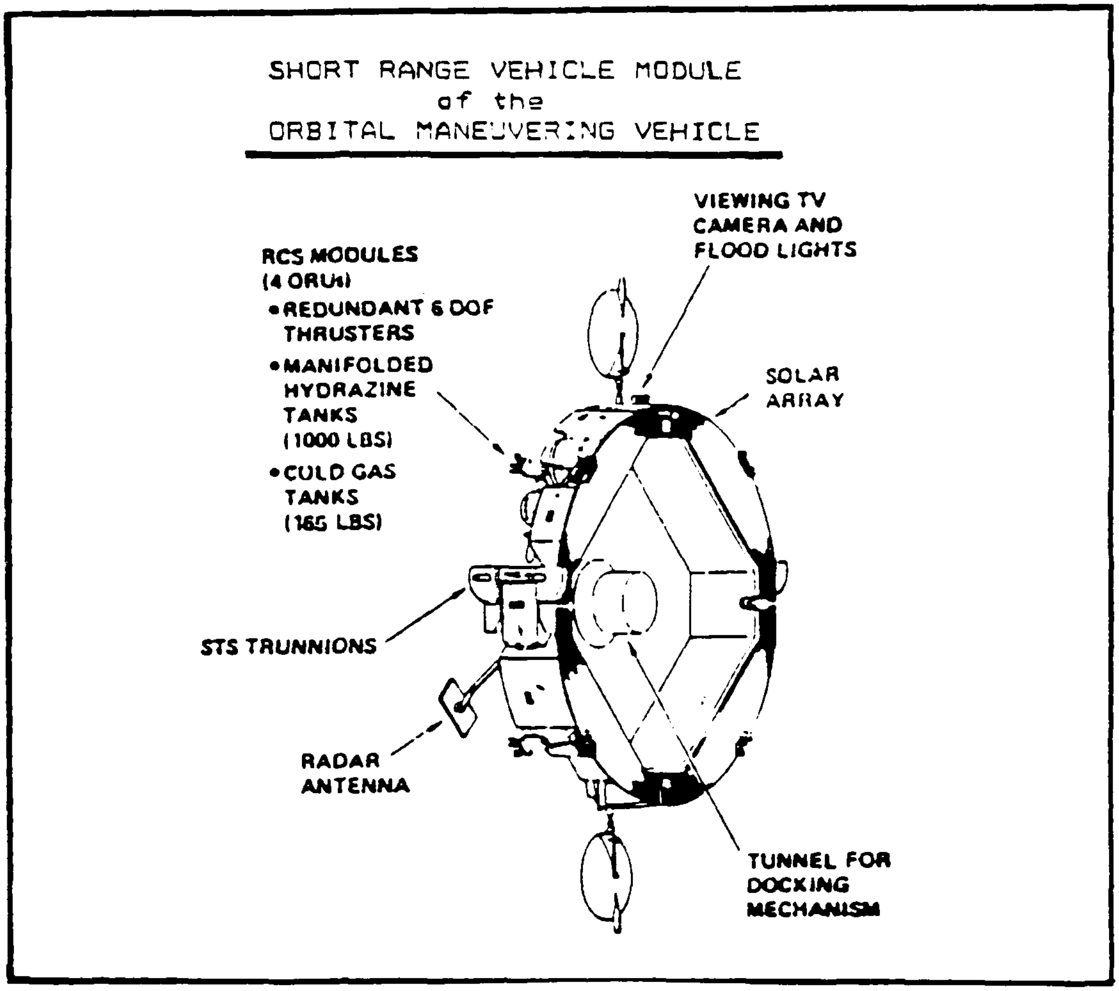


Fig. 15. Long Range Subsystem (27:4)

<u>Summary.</u>

The example rescue/recovery system presented above provides for a layered systems approach to the problems of EVA crew rescue and equipment recovery. This systems approach begins with prevention and ends with complementary reactionary subsystems which accomplish the objectives. Each subsystem is designed to operate primarily within a given

range category. However, they can also operate closer to the space station. This flexibility allows all the subsystems to complement and assist each other in any rescue/recovery operations. This example rescue/recovery system shows the value of a systems approach to solving the problems of EVA crew rescue and recovery of detached and adrift equipment from the space station. With the presentation of this example rescue/recovery system complete, the conclusions, recommendations, and issues found during the development of this thesis can now be presented.

VI. Conclusions, Recommendations, And Issues

This chapter presents the conclusions, recommendations, and issues which were generated during the development of this thesis. The conclusions are drawn from the work done in the thesis. The recommendations are several areas which require further examination. The issues are discussions of outstanding areas of concern which relate directly to the problems of EVA crew rescue and recovery of detached and adrift equipment from the space station, but are outside the scope of this thesis.

Conclusions.

The conclusions of this thesis deal with the process and results of the work. Specifically, the methodology used and the results of the analysis are the areas of key interest.

The methodology used in this analysis coupled several techniques. It used both concept mapping (basically a teaching tool) and the Analytic Hierarchy Process within the Hall Morphology of Systems Engineering. This methodology proved to be quite easy to understand and use. Concept mapping was the key to the whole methodology. The ability to capture the important concepts, all their facets and interrelationships proved to be the key to understanding the problems and structuring the analysis. For this type problem, one very much in the early conceptual development

stage, concept mapping proved to be a useful tool in gathering a comprehensive understanding of the problem. This tool served as the backbone for the rest of the analysis, in that the evaluation criteria and breakdown of system types were directly derived from it. Therefore, one of the conclusions from this thesis is that the methodology, especially concept mapping, is a powerful technique to use in defining the direction to take for problems which are early in the concept development stage.

The second conclusion of this thesis deals with the results of the analysis itself and with the direction to be taken in the solutions to the problems of EVA crew rescue and recovery of equipment which becomes detached and adrift from the space station. Specifically, the conclusion is that there is no one device which will solve these problems. Rather these problems can only be solved through a systems engineering approach where several subsystems contribute to the overall solution. These subsystems serve to complement and back up each other in order to increase the probability of successfully accomplishing a rescue or recovery. The recommended system from this analysis consists of an EVA self rescue subsystem, a space station supported subsystem, an unmanned free-flyer subsystem, and the OMV. In addition to these conclusions, there are several recommendations which should be addressed as future considerations to the problems of EVA crew rescue and equipment recovery.

Recommendations.

There are three areas where further analysis is recommended. The first has to do with this thesis effort itself. The other two areas relate to subjects whose analysis is required as follow-on efforts to this thesis.

The first recommendation is that this thesis effort, being a first cut analysis, should be part of an iterative analysis. Specifically, this iterative analysis should concentrate on the concept map. This iterative review should be accomplished to better develop a corporate understanding of the problem and to better define the evaluation criteria. The results of this iterative analysis may well point to a specific solution system to the problems, rather than to just indicate the path to take toward that solution. Additionally, this iterative analysis should take into account the results of the two complementary areas where further analysis is recommended.

The first of these complementary areas is that of analyzing the necessity of a long range subsystem for the rescue/recovery system. This analysis seeks an answer to the question "does the incorporation of a long range subsystem add enough value to the comprehensive rescue/recovery system to warrant its expense?" Included in this analysis are considerations about the probabilities of the short and medium range subsystems failing, the probability of the long range subsystem succeeding, and the overall costs of such a

long range subsystem. Included in this analysis should be an investigation of the worth of the medium range subsystem. This analysis should answer the question of "can the medium range subsystem be replaced by a more capable (and more expensive) long range subsystem?" The answers to this complementary analysis may well limit the number of rescue/recovery systems which need to be examined.

The other complementary analysis to this thesis deals with the rescue/recovery systems configuration during the construction of the space station. One of the comments received as feedback to the comprehensive concept map indicated that the space shuttle would be available for rescue/recovery operations during the construction of the space station (36). Indeed, the space shuttle will be present during the construction, but availability for rescue/recovery operations may well be another issue. The shuttle could be tied up in the construction of the space station to the point where its response time would make it an unusable option. Therefore, this complementary analysis should address the rescue/recovery systems configuration during the construction of the space station and how this configuration would change when the space station becomes operational (it may be possible to design one rescue/recovery system to be used during both the construction and the operations phase of the space station).

These recommended complementary analyses will help further examine the topics of this thesis. However, there are issues which require examination that are beyond the scope of this thesis, but still contribute to the solution to the problems of EVA crew rescue and equipment recovery.

Issues.

There are two major issues which are beyond the scope of this thesis, but still require examination. These issues are: 1) how to make the decision to recover adrift equipment, and 2) when to use or not use a manned free-flyer (like the MMU) for rescue/recovery operations if such a system is readily available.

The first issue deals with the basic question of when to recover adrift equipment. If the decision is that all loose equipment must be recovered, then this issue becomes a moot point. But, if only selective equipment is worthy of recovery, then on what criteria will the decision be made? Obviously, the value of the equipment (both cost and ease of replacement) and the departing trajectory of the object will play a role in the examination of this issue. However, the value of the equipment and the costs associated with a recovery attempt also need to be examined.

The second issue deals with the use of a manned free flyer (like the MMU) to perform rescue/recovery operations. This thesis has concluded that the preferred direction to be

taken is toward an unmanned free-flyer. However, manned free-flyers will be present at the space station. (Current planning calls for the space station to be configured with at least one next generation MMU (15:4-33).) This free-flyer may be in use when a rescue/recovery opportunity presents itself. This issue wrestles with the decision to use or not use a manned free-flyer for rescue/recovery operations. It seems apparent that if a manned free-flyer is in use, it could be used for a rescue or recovery, but there appear to be limits to its use. Obvious limits are the pilot's consumables and the amount of fuel in the free-flyer. These limits change as the EVA progresses. Therefore, it seems that there are time frames when a manned free-flyer could be used for rescue/recovery operations and there are also time frames when no matter what the object requiring rescue/recovery is (another astronaut or piece of equipment) a manned free-flyer will not be used because it jeopardizes the pilot's safety. This is another of the issues which requires examination in order to fully understand the problems of EVA crew rescue and equipment recovery.

Summary.

This thesis has helped answer several questions. It has provided the direction to be taken in solving the problems of EVA crew rescue and equipment recovery. It has also shown a methodology which can be used in the systems engineering of

problems during their concept development stage. But, this thesis has also asked questions. It asks questions and recommends further study in the areas of iterating the analysis, determining the value of both the long range and medium range subsystems, and identifying the changing rescue/recovery system from the construction to the operations of the space station. This thesis also asks far reaching questions as to the decisions to recover adrift equipment and to the use of a manned free-flyer in rescue/recovery operations. The problems of EVA crew rescue and recovery of detached and adrift equipment from the space station are complex. Hopefully this thesis has shed some light on them.

A. Initial Pre-Concept Map Survey.

NOTE: The purpose of this survey was to focus the attention of the persons to be concept mapped into the areas of EVA crew rescue and recovery of detached and adrift equipment. The results of this survey are informational to the perception of the problems, but do not affect the analysis performed.

NAME:

EVA Crew Rescue
and
Retrieval of Detached and Adrift Equipment

Initial Survey

The purpose of this survey is to determine the relationships between the problems of EVA Crew Rescue and Retrieval of Detached and Adrift Equipment from the Space Station.

Importance:

Which problem do you feel is the most important? a) EVA Crew Rescue b) Retrieval of detached and adrift equipment.

Indicate on the scale below the relative importance between these two problems.

EVA Crew Rescue	8	6	4	2	0	2	4	6	8	Retrieval of Detached and Adrift Equipment
	Absolute Importance	Very Strong Importance	Strong Importance	Weak Importance	Equal Importance	Weak Importance	Strong Importance	Very Strong Importance	Absolute Importance	

Probability of Occurrence:

Which problem is more likely to occur? a) EVA Crew Rescue b) retrieval of detached and adrift equipment

How much more likely is this problem to occur as opposed to the least likely problem? a) Very much more likely b) Much more likely c) More likely

Relationships:

Indicate which statement you most agree with:

a) The problems of EVA Crew rescue and retrieval of detached and adrift equipment are two separate unrelated problems.

b) The problem of EVA Crew Rescue is a subset of the problem of retrieval of detached and adrift equipment.

c) The problem of Retrieval of detached and adrift equipment is a subset of the problem of EVA Crew Rescue.

Do you feel that one system can be used to solve both problems? a) yes b) no

If you feel one system can be used to solve both problems, which problem would you concentrate your efforts on? a) EVA Crew Rescue b) Retrieval of detached and adrift equipment

Comments:

B. Analytical Hierarchy Process Survey.

NOTE: The purpose of this survey was to obtain feedback on the Consolidated Concept Map and to obtain the pairwise comparisons for the evaluation criteria to be used in the weighing function of the analysis.

EVA Crew Rescue and Retrieval of Detached and Adrift Equipment Concept Map and AHP Survey

Part 1: Consolidated Concept Map

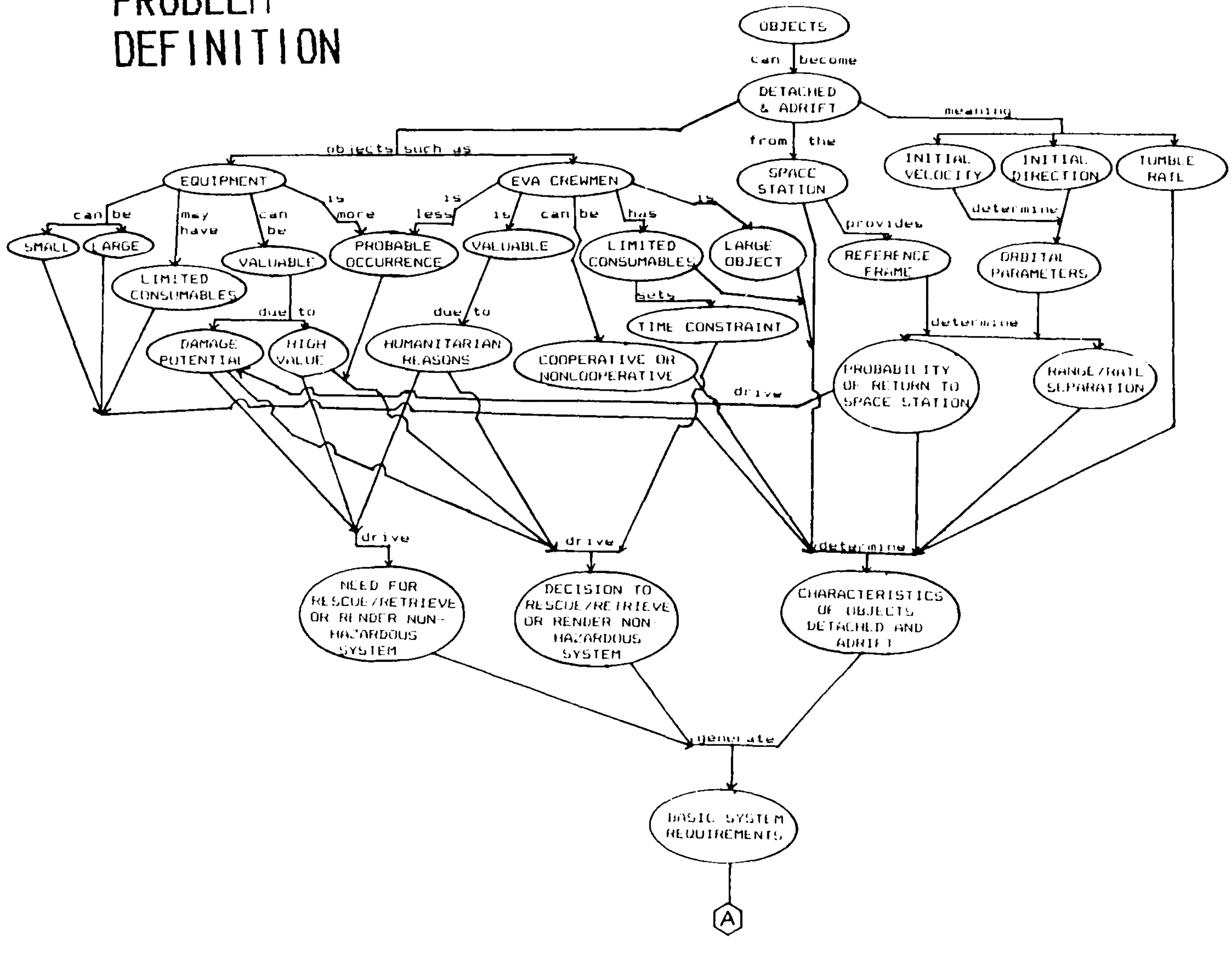
Purpose: The purpose of this section of the survey is to obtain your feedback on the consolidated concept map. This map was generated by consolidating all the concept maps obtained during the interviews of 8-11 July 1987.

Feedback Process: The consolidated concept map is divided into three sections: Problem Definition, Value System Design, and System Synthesis. These three sections are actually the first three steps in solving any problem: first you identify the problem, then determine the key drivers of the problem, and finally develop alternate solutions to the problem. I request that you look at this consolidated concept map in that light and determine if the map "captures" the problem. Feel free to make any corrections, additions, or subtractions to this map as you see fit (you may write on it to your heart's content).

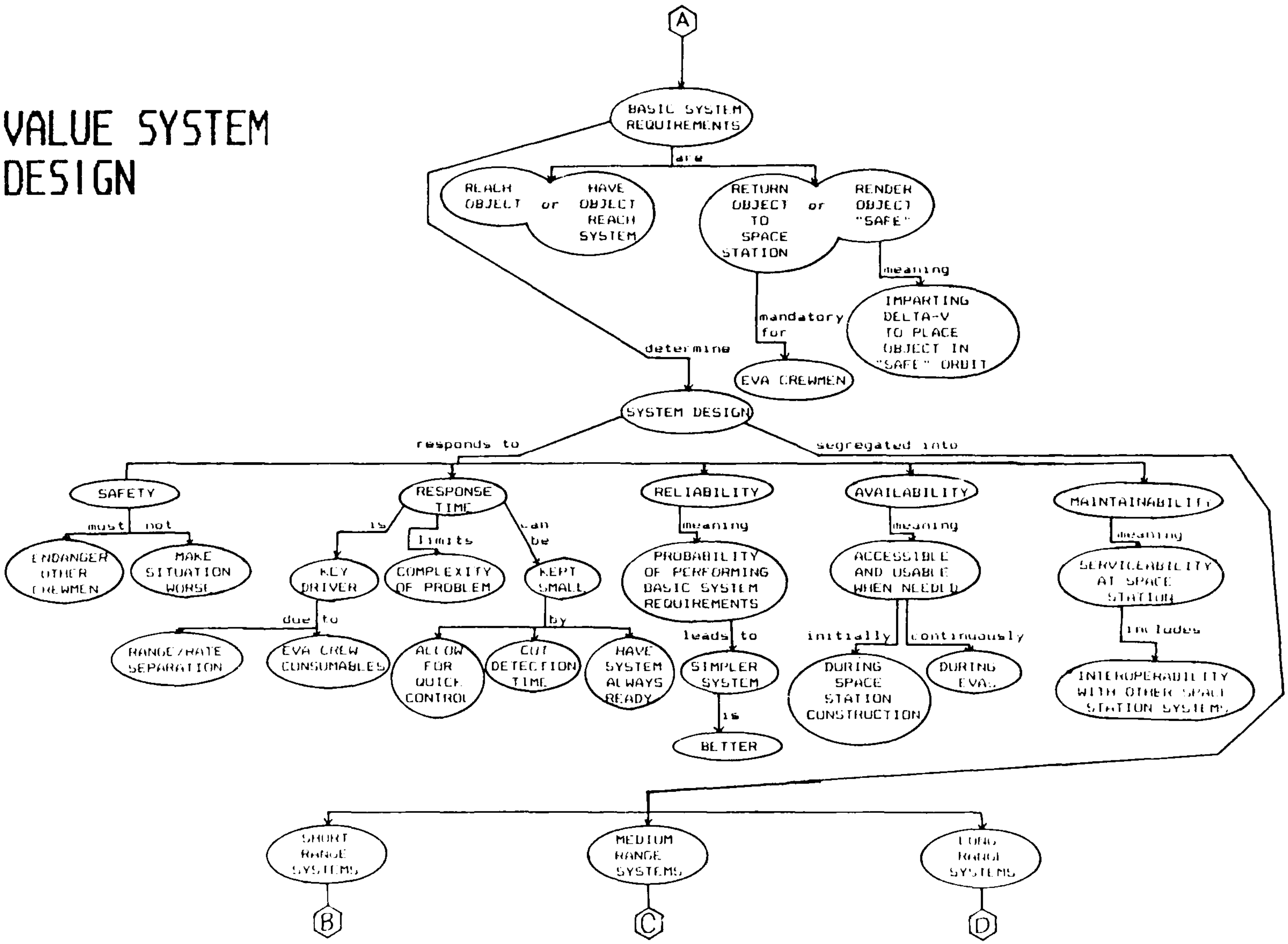
Additionally, I would be interested in any comments you have about the technique of concept mapping in general. Do you feel it is a valuable technique (it helps capture the problem) or is it just BS? I have provided space for your comments below.

Comments:

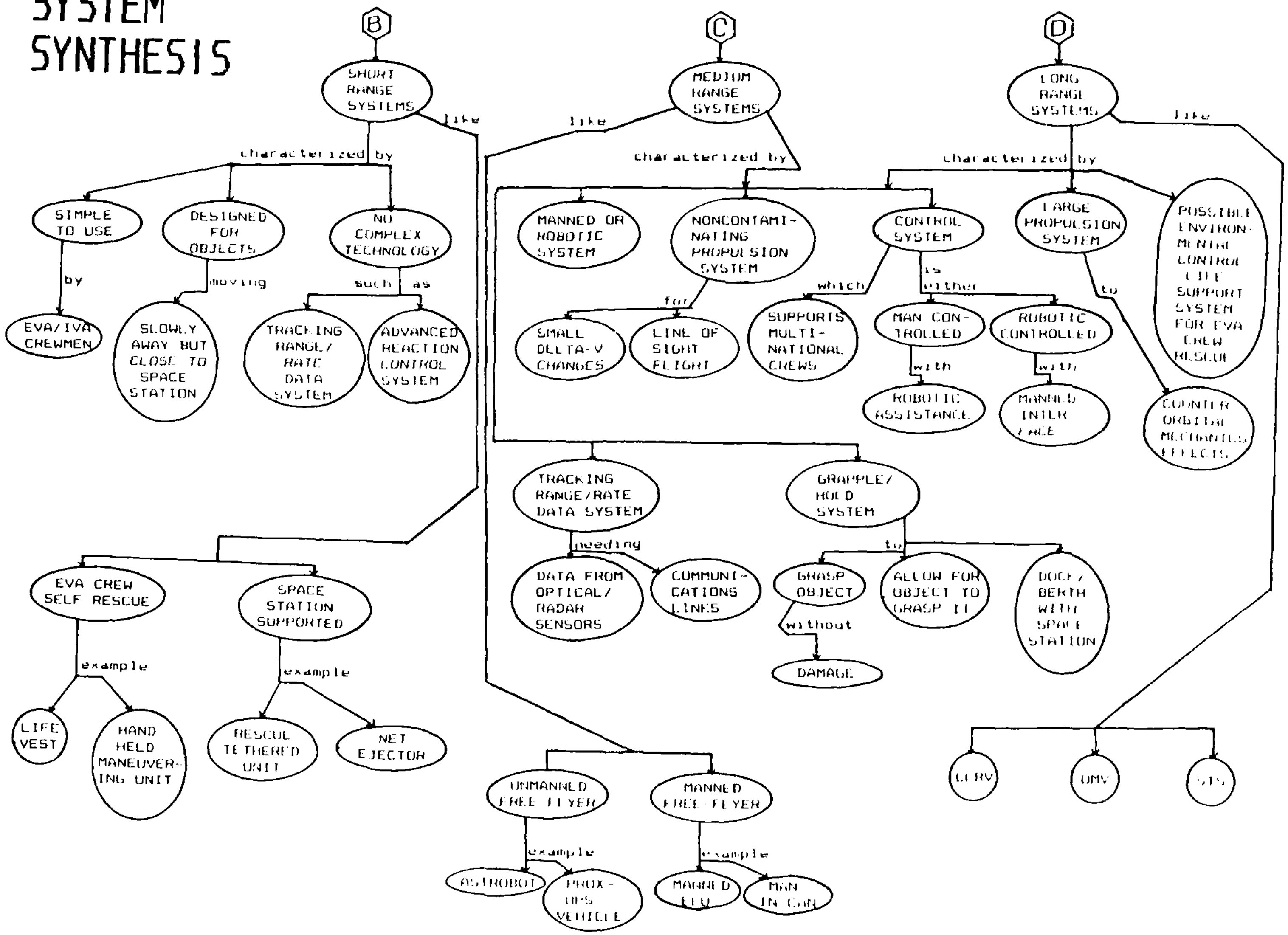
PROBLEM DEFINITION



VALUE SYSTEM DESIGN



SYSTEM SYNTHESIS



EVA Crew Rescue and Retrieval of Detached and Adrift Equipment Concept Map and AHP Survey

Part 2: Attribute Assessments

Purpose: The purpose of this section of the survey is to obtain your assessment and prioritization of selected system attributes. These attributes were generated directly from the consolidated concept map and will be used to evaluate the various candidate rescue/retrieval systems which help solve the problem.

Survey Process: This part of the survey is based on the Analytical Hierarchy Process (AHP) developed by Thomas L. Saaty. This process solicits a preference choice between paired attributes and builds these choices into an overall attribute weighting function.

Your involvement in AHP is to rate given pairs of attributes according to a provided scale (see Table IX). These attributes will be rated according to the importance of the first attribute to the second attribute in solving the problem of EVA crew rescue of equipment retrieval.

If you feel the first element in a pair (Attribute A) is more important than the second element (Attribute B), then a positive number from the scale should be used. Conversely, if you feel the first element (Attribute A) is less important than the second element (Attribute B), then a negative number from the scale should be used. To illustrate this rating system, I have included the following example which deals with the problem of making pop corn.

> Suppose you are asked to rate the importance of good quality pop corn (Attribute A) to that of a constant source of heat (Attribute B) in the making of pop corn. If you feel the Attribute A (the quali[illegible] of the corn) is favored very strongly over Attri[illegible] (the constant heat source) in the process of po[illegible] corn, then you would assign a value of +7 to [illegible] pairwise comparison. However, if you feel [illegible] Attribute B (the constant heat source) is [illegible] more important than Attribute A (the [illegible] corn) in the process of popping corn, [illegible] assign a value of -3 to that pairw[illegible]

Remember the following rule:
If Attribute A is more [illegible] positive numbers. But if Attri[illegible] Attribute A, use negative [illegible]

AD-A189 683 AN EVALUATION OF THE METHODS FOR RESCUING EVA (EXTRAVEHICULAR ACTIVITIES)..(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI.. T SELINKA 2/2

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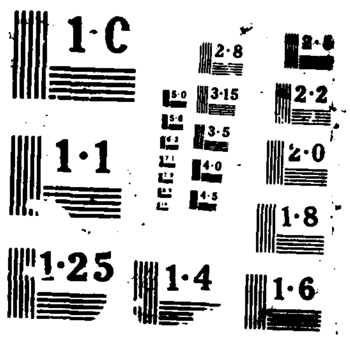

1·1
1·25
1·4
1·6
1·8
2·0
2·2
2·8
3·15
3·5
4·0
4·5

TABLE IX

AHP COMPARISON SCALE

Numerical Rating	Definition	Explanation
1	Equal importance	Two attributes contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favor one attribute over the other
5	Essential or strong importance	Experience and judgement strongly favor one attribute over the other
7	Very strong or demonstrated importance	An attribute is favored very strongly over another; its dominance has been demonstrated
9	Absolute importance	Evidence favoring one attribute over another is of highest possible order
2,4,6,8	Intermediate values	When compromise is needed

Additionally, these pairwise comparisons are independent of each other. The ratings of one pairwise comparison should not influence the ratings of the next pairwise comparison.

The question to be answered in doing these pairwise comparisons is: Given the objective of finding the best way to rescue EVA crewmembers and/or retrieve detached and adrift equipment from the space station, how much more strongly does Attribute A influence the selection of a Rescue/Retrieval System than does Attribute B ?

Attribute Definitions:

Safety: This attribute is difficult to define. However, in this case we shall consider it to be the freedom the Rescue/Retrieval System provides from making the situation worse or from endangering other crewmembers. For example, we might say that a system has a 98% chance of not making the situation worse.

Response Time: This attribute is the time it takes for the system to detect the separation of an object and begin the physical process of returning or rendering the object "safe." In the case of a free-flyer, response time is the time from object separation from the space station to the Rescue/Retrieval systems separation from the space station.

Reliability: This attribute is defined as the probability that the Rescue/Retrieval system will successfully perform its' basic function of reaching the object (or having the object reach it) and return the object to the space station or render the object "safe" (meaning it will not pose a threat to the space station).

Availability: This attribute is the accessibility of the system and its' being usable when needed. For example, if the system is required to be available 90% of the time, then it can be "down" for repairs 10% of the time. The trick is to insure that the system is not "down" when needed.

Maintainability: This attribute is a measure of the serviceability of the Rescue/Retrieval system. It is traditionally a measurement of the time it takes to repair or service the system.

Pairwise Comparison:

Remember:

- Use the scale found in Table 1
- If Attribute A is more important than Attribute B use positive number
- If Attribute B is more important than Attribute A use a negative number
- The key question is: Given the objective of finding the best way to rescue EVA Crewmembers and/or retrieve detached and adrift equipment from the space station, HOW MUCH MORE STRONGLY DOES ATTRIBUTE A INFLUENCE THE SELECTION OF A RESCUE/RETRIEVAL SYSTEM THAN DOES ATTRIBUTE B ?

Survey Itself:

ATTRIBUTE A	ATTRIBUTE B	RATING
Safety	Response Time	
Safety	Reliability	
Safety	Availability	
Safety	Maintainability	
Response Time	Reliability	
Response Time	Availability	
Response Time	Maintainability	
Reliability	Availability	
Reliability	Maintainability	
Availability	Maintainability	

☐ Check this box if you would like a copy of this thesis sent to you. It will be available in January 1983.

THANK YOU ! ! ! !

C. Survey Results.

The results of the AHP Attribute Assessment Survey are provided below. The geometric mean was calculated on the raw data to develop the pairwise comparison matrix. For the pairwise comparisons: S=Safety, RT=Response Time, R=Reliability, A=Availability,and M=Maintainability.

TABLE X

SURVEY RESULTS

Pairwise Comparisons	Raw Data							Geometric Means
S - RT	1	7	3	-3	9	7	5	3.00
S - R	-9	5	1	2	9	7	-3	1.56
S - A	-7	5	1	4	9	7	3	2.46
S - M	9	6	1	6	9	7	5	5.19
RT - R	-9	5	-3	3	1	-3	-3	0.67
RT - A	-5	3	-3	5	1	-3	1	0.85
RT - M	7	5	-3	6	7	-3	3	2.42
R - A	1	1	1	4	1	5	5	1.93
R - M	9	7	1	6	7	5	5	4.88
A - M	9	5	1	3	7	5	5	4.21

$$\text{Geometric Mean} = \left(\prod_{i=1}^{n} a_i \right)^{1/n} \qquad i=1,2,\ldots,n$$

In AHP -7 = 1/7. Thus, for the raw data of 7,5,-3,6,7, -3, and 3; the geometric mean is:

$$(7 * 5 * (1/3) * 6 * 7 * (1/3) * 3)^{1/7} = 2.42$$

D. Review of Contractor Proposed Solution Systems

This appendix reviews the NASA provided contractor proposed solution systems to the problems of EVA crew rescue and equipment recovery. These proposed systems represent the concept synthesis (brainstorming) section of the Hall Morphology of Systems Engineering. As such, they are limited in the technical description and they do not present a systems engineering solution to the problem, but rather individual subsystems which could be a portion of an overall rescue/recovery system.

Contractor Proposed Solution Systems

Short Range Contractor Proposed Systems

Numerous contractor concepts were presented for short range rescue operations. Many dealt with assisting EVA's rather than with crew rescue or equipment recovery. These were eliminated from consideration in this thesis. Additionally, many of the contractor concepts were repetitive ideas. A consolidated concept will be reviewed in these cases. The short range systems can be broken down into EVA Self Rescue Systems and Space System Supported Systems.

EVA Self Rescue Systems. These systems have an astronaut who is floating away rescue himself. The contractor proposed solution concepts are as follows.

Hand Held Propulsion Device. This device is a continuation of the hand held propulsion devices tested during the Gemini and Skylab programs. The advantages of this device are relatively low cost, but disadvantages include the devices difficulty to control, added bulk for EVA crewman, and a cooperative astronaut being required (21:11).

Portable Aerosol Jet. This device is an aerosol gas can which mounts on any structure and can have its' nozzle positions controlled by radio link (18:3). Advantages are in low cost, but disadvantages occur in safety, reliability, and ease of use (18:23).

Safety throw line/rescue line. These are systems where the astronaut requiring rescue attempts to attach a line to the space station. Advantages are low cost. Disadvantages are low reliability, safety, and ease of use (18:23).

Telescope Pole Hook. This device uses a pole with hook to grasp the space station. Then the astronaut requiring rescue pulls himself in. The advantage and disadvantages for this device are much the same as for the safety throw line (18:23).

Space Station Supported Systems. These are short range systems which require someone other than the astronaut requiring rescue to operate. These contractor proposed solution are as follows.

Safety Net/EVA Net Enclosures. This system calls for safety nets to be deployed around the area where EVA is to occur. While, these systems are low cost, and provide a positive enclosure, they are difficult to install and could complicate crew operations (21:10). However, for special projects, like building a spacecraft in orbit for a martian mission, these nets may well prove of great value in reducing lost items and protecting the vehicle being built.

Redundant Tethers/Double Tethers. This device calls for the use of the tethers, redundant to the current one, for EVA operations. This system has the advantages of

positive capture, but disadvantages are in crew discomfort and increased the time for connection and disconnection of the system. Astronauts do not consider this an acceptable system (21:10).

Boom Extender. This system is an extendable/ retractable boom structure which provides a means for EVA crewmember stabilization for rescue (see Figure 16) (19:5;18:4). The system has low safety and limited flexibility (18:23).

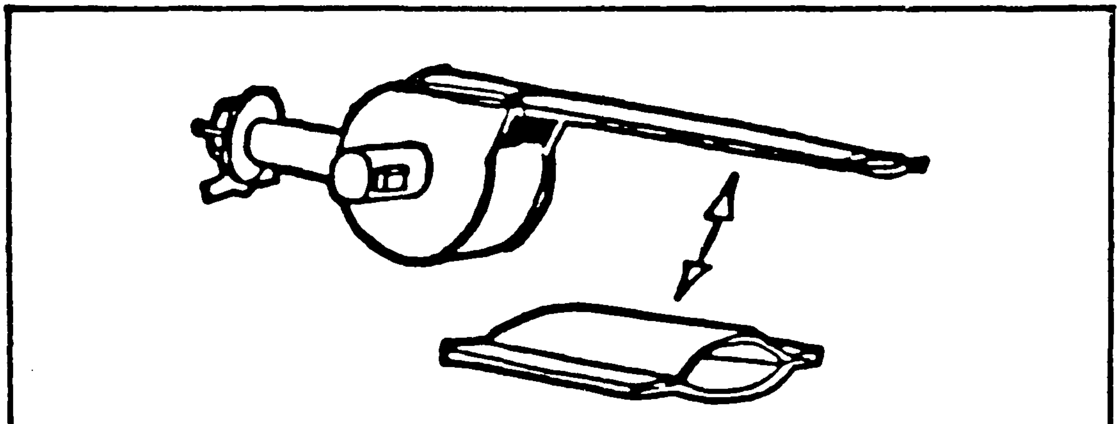


Fig. 16. Boom Extender (19:3)

Mobile Remote Manipulation System (MRMS). This system is the space station version of the successful space shuttle RMS. The system has the remote manipulator system like the shuttle (for capture/grasping of object) but can also transverse along the space station (Figure 17) (19:5). Advantages are the systems safety, ease of use, and

dexterity. Disadvantages are the slow response time (18:23).

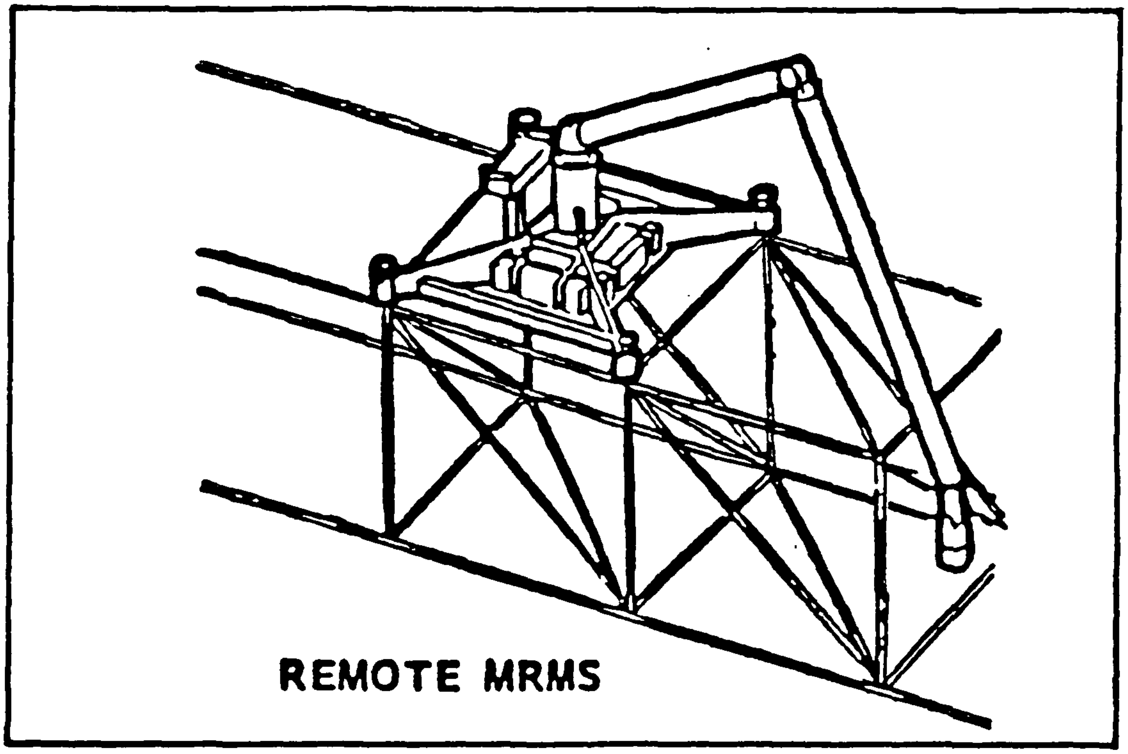


Fig. 17. MRMS (19:4)

<u>Smart End Effector for MRMS</u>. This system is an automated robotic manipulation and service unit attached to the Remote Manipulator Arm (19:5). Although this system has the same range and response time limits as the MRMS. The addition of the smart end effector does allow for the easier grasping of objects by the MRMS.

<u>Net Ejector System</u>. This is a rescue device which propels a blanket netting towards a stranded EVA crewmember allowing him to restrain himself to the netting as it is retracted back to the space station (Figure 18) (19:5). The

advantages of this system and its response time and simplicity. However, it has problems in that it requires a cooperative astronaut and that when the net hits the astronaut, it exerts an unpredictable force on the astronaut. This force could well make the situation worse by propelling the astronaut away from the space station or by causing injury to the astronaut.

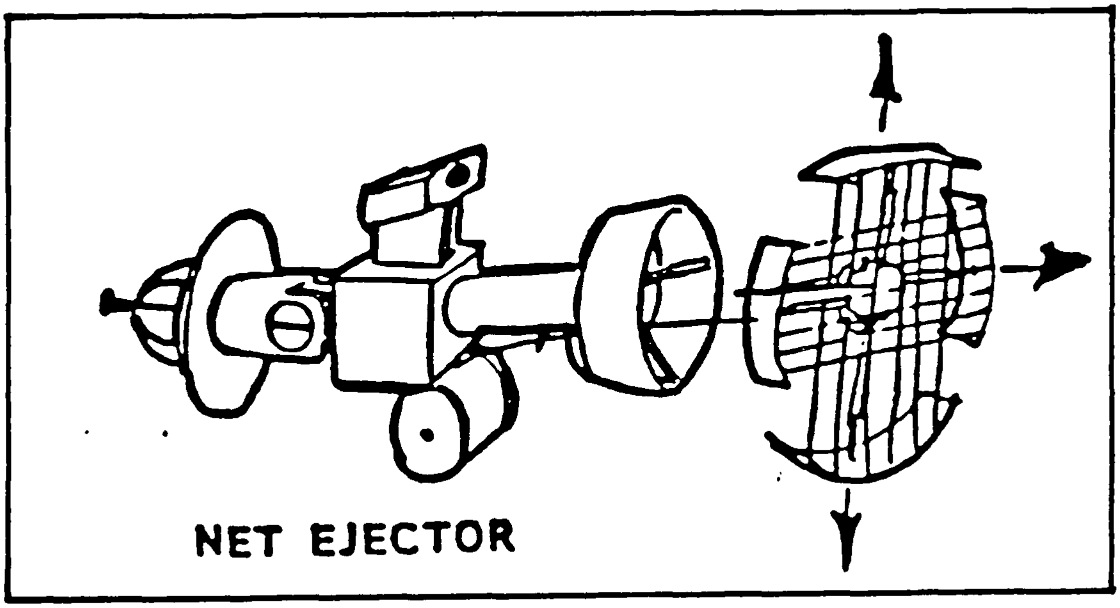


Fig. 18. Net Ejector System (19:3)

<u>Rescue Tethered Unit/Guided Tether</u>. This system consists of a self reeling tether attached to a free-flying unit. This system flies out to the astronaut requiring rescue, allows the astronaut to grasp it, and then reels itself back to the space station (Figure 19)(19:5). The advantages of this system are its ease of use, low technical risk, and positive attachment to the space station.

Disadvantages are that the drifting astronaut must grasp the system and that the system has no capability to capture drifting objects (18:23).

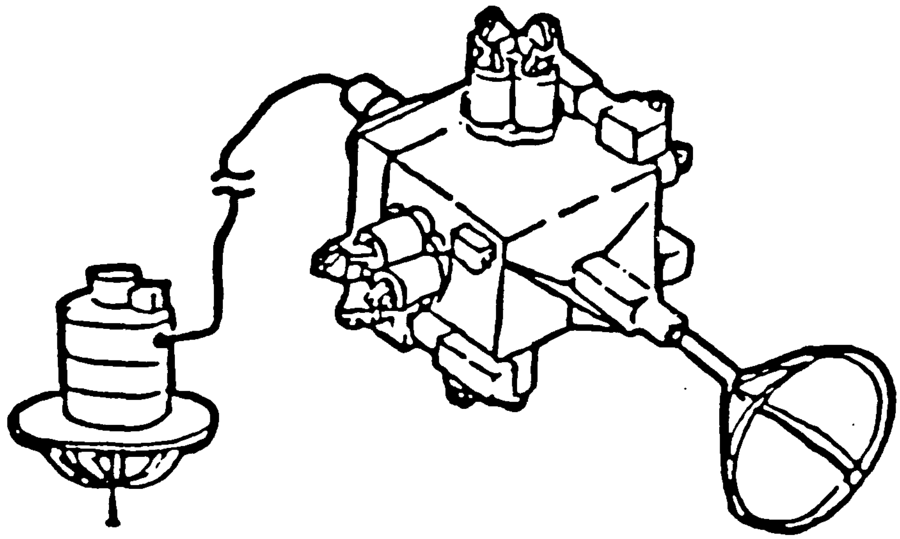
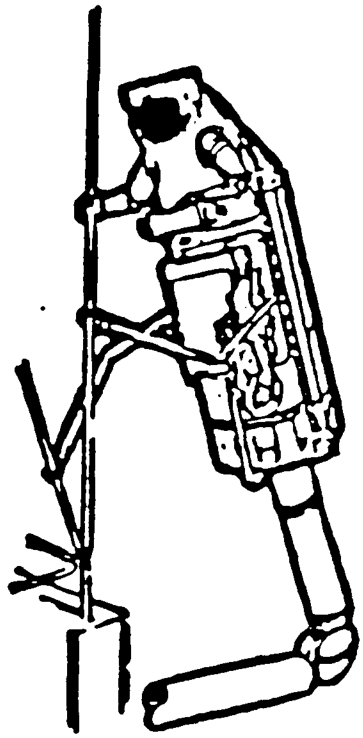


Fig. 19. Rescue Tethered Unit (19:3)

Enclosed Cherry Picker. This system, attached to the MRMS, provides a pressurized environment for a crewmember to operate the attached manipulator arms/ends effectors and gloved hand manipulative capability (Figure 20)(19:5). This system has the same maneuvering and range limitation of the MRMS, but also the flexibility and dexterity of being a manned system.



ENCLOSED CHERRY PICKER

Fig. 20. Enclosed Cherry Picker (19:4)

<u>Open Cherry Picker</u>. This system is like the enclosed cherry picker having the same manipulator arms and being attached to the MRMS, but it is operated by an EVA astronaut (Figure 21)(19:5). The advantages and disadvantages for this system are very much like the enclosed cherry picker system. However, this open system is less complex because it does not need to provide a pressurized environment.

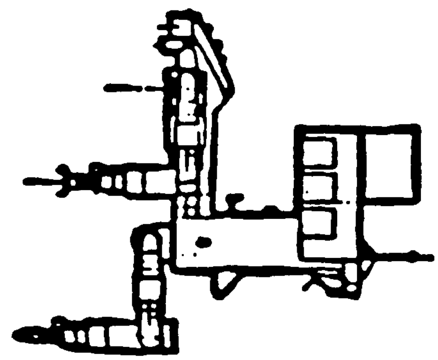


Fig. 21. Open Cherry Picker (19:4)

Rescue Line/Life Ring. This system is much like the EVA self rescue safety throw line, except in this case, the rescue line is propelled to the drifting astronaut by a second EVA astronaut (18:3). This system is similar to the life ring buoys found on ships. The advantages of this system is its simplicity and ease of use. Disadvantages are its uncontrollability and low reliability (18:23).

Medium Range Systems.

These contractor proposed systems are designed to operate within the proximity operations zone around the space station. These systems are free-flyers of the unmanned and manned type.

Unmanned Free-Flyers. All these systems use a robotic system designed to perform rescue/recovery operations. As such many are similar to the EVA Retriever. Such systems are the Generic Space Robot, and Astrobot (which will be examined together).

Generic Space Robot and Astrobot plus EEU. These robotic systems, have a robot driver mated to either the MMU or Extravehicular Excursion Unit (EEU). (The EEU is basically an updated version of the MMU which has greater fuel capacity.) Both these robotic free-flyers come complete with grasping manipulator arms and remote control sensors (television cameras). The difference between them is that the Generic Space Robot also has provisions for an automatic center of mass compensator (this allows for more efficient use of fuel). Figure 22 shows the basic configurations of these systems. Advantages of this type system are its safety, quick response time, versatility, and multiple mission applications (18:10). Disadvantages are their limited ability to recover small drifting objects.

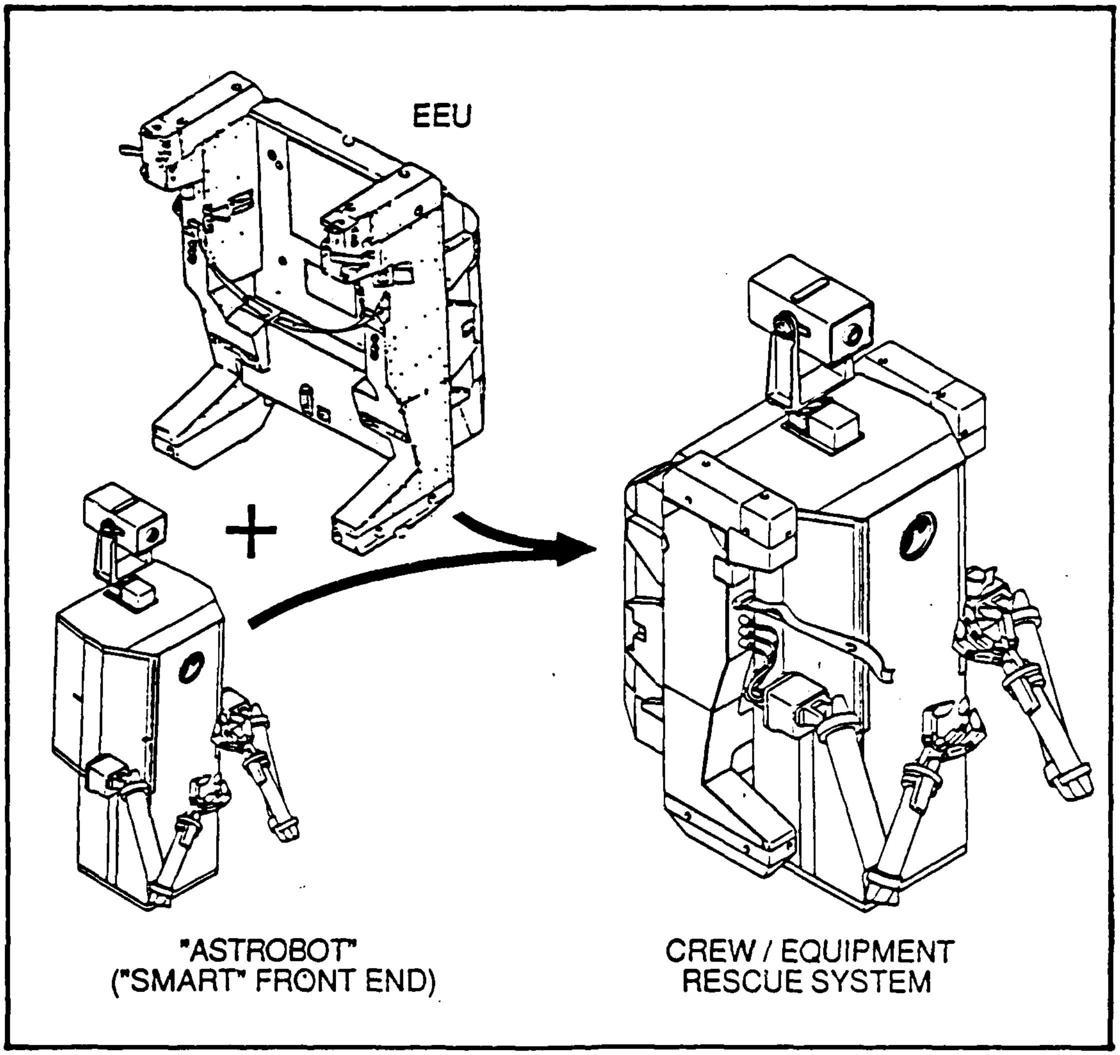


Fig. 22. Astrobot plus EEU (20:8)

<u>Telerobotic Vehicle</u>. This system call for a remote controlled free-flyer like the one shown in Figure 23. This system uses a cold gas propellent system and is designed to either grasp the object, with a manipulator arm or have an astronaut requiring rescue grab and hold onto it (21:18). The advantages of this system is its safety and relatively

large amount of usable propellant. Disadvantages are in its limited applications in recovering drifting objects, and its low reliability in recovering noncooperative astronauts.

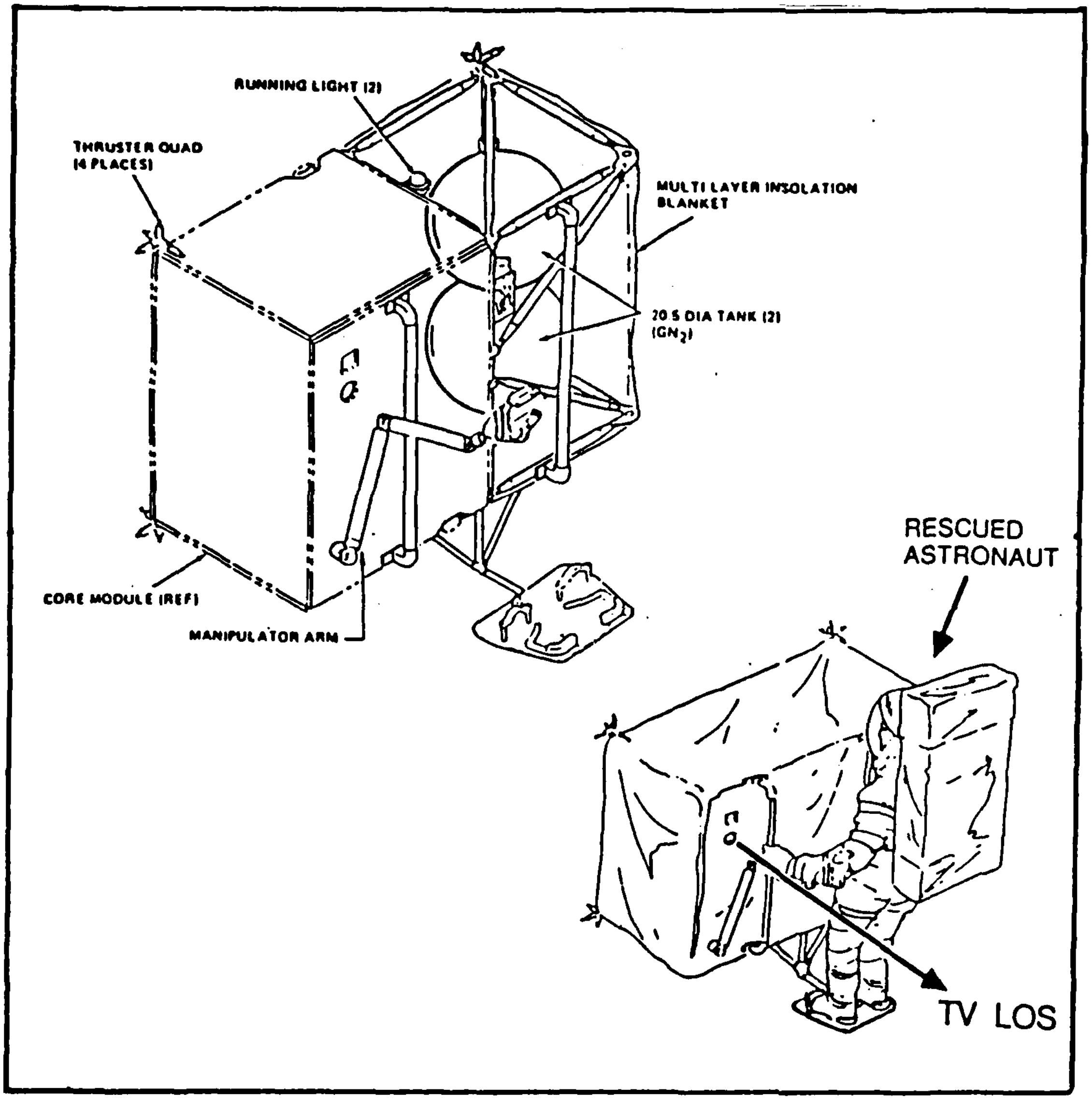


Fig. 23. Telerobotic Vehicle (20:9)

Prox-Ops-Vehicle. This vehicle, shown in Figure 24, is a remotely controlled free-flyer which is designed

primarily to perform the satellite servicing function done at the space station, however, it can also perform rescue/recovery operations (19:2). This system has advantages of safety, quick response time, and maneuverability. Its disadvantages are its high cost and low reliability (18:23).

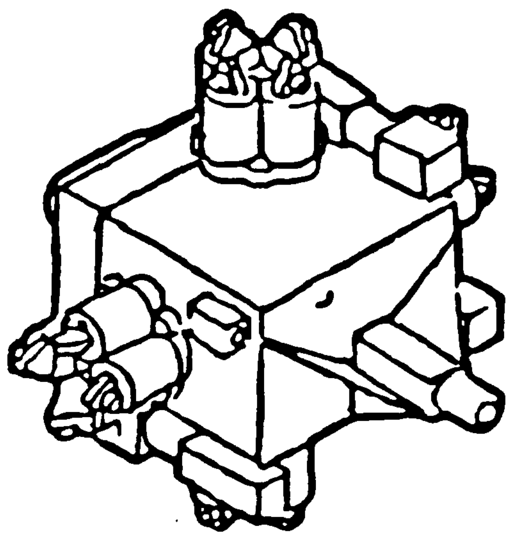


Fig. 24. Prox-Ops-Vehicle (19:1)

Free-Fly Independently Directed Excursion Unit. This is a tele-operated robotic system with smart front end consisting of video camera, manipulator arms, and the processing/analyzing necessary to carry out space station EVA functions (See Figure 25) (19:2). This system has the same

advantages and disadvantages as do the Generic Space Robot and Astrobot. Its only difference is that it does not use the MMU or EEU as its propulsion unit.

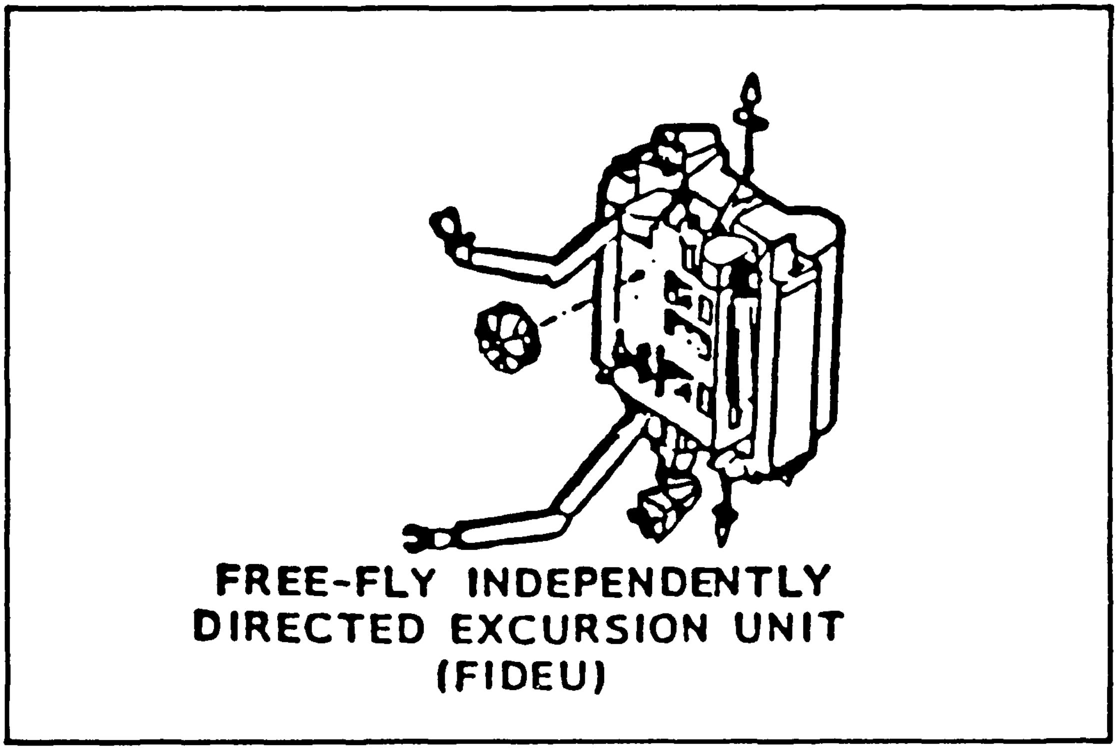


Fig. 25. Free-Fly Independently Directed Excursion Unit (19:1)

<u>Manned Free-Flyers</u>. These contractor proposed manned systems are designed for rescue/recovery operations within the prox-operations zone of the space station.

<u>Manned Maneuvering Unit (MMU)</u>. This manned system consists of a self-contained backpack with all the necessary systems to allow an EVA astronaut to fly untethered in space of a short distance from the space station or space shuttle (40:1). This system has been flown on several space shuttle

mission and is a proposed rescue/recovery system (19:2). Flight experience and simulation results indicate that this system can be used for an orbit rescue/recovery operations (31:2). However, because this is a manned system, its use does jeopardize an additional EVA astronaut and thus the decision to use the MMU needs to be carefully thought out. Figure 26 shows a representation of the MMU performing EVA crew rescue.

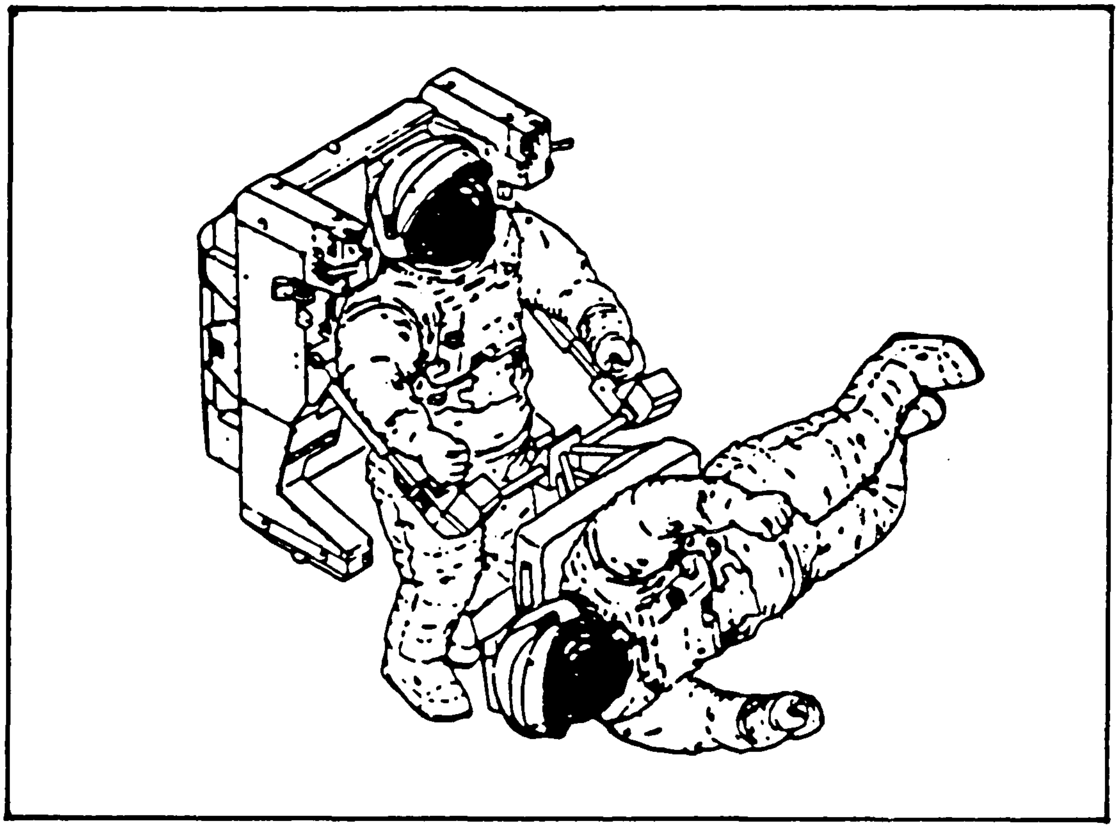


Fig. 26. MMU EVA Crew Rescue (31:6)

Extravehicular Excursion Unit (EEU). This manned system is the next generation of the MMU. Its major change

is the greater fuel capacity it possesses (20:7). This system (Figure 27) has the same advantages as the MMU except that it can perform rescue/recovery operations at a greater range. However, it also suffers the same disadvantages (manned system and slow response time) (20:10).

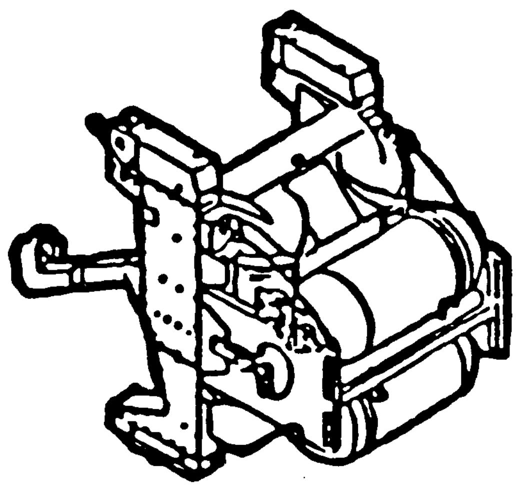


Fig. 27. Extravehicular Excursion Unit (19:1)

Homing Unit Plus EEU. This system calls for a caution and warning sensing unit to be attached to the EEU. This sensor would alert the EVA crewmember when he/she enters a zone which is out of the rescue range of any of the space station supported rescue system (Figure 28) (19:2). Advantages of this system are its low cost, reliability,

maintainability, and serviceability. Disadvantages are that it is only a warning device, not capable of actually performing rescue (18:23).

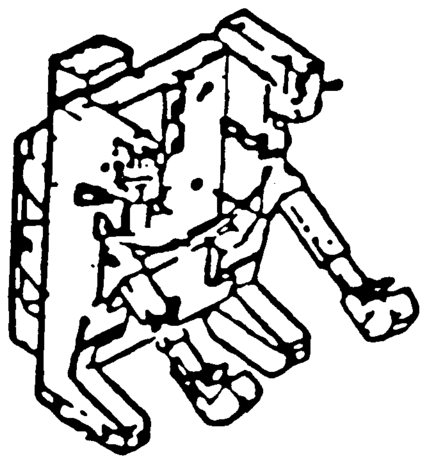


Fig. 28. Homing Unit Plus EEU (19:1)

Man-In-Can. This manned rescue/recovery system is a detached version of the Enclosed Cherry Picker (see Figure 29). As such, it still provides the pressurized environment, end effectors, and gloved hand manipulative capacity of the cherry picker, but also has propulsion units to provide for maneuvering around the space station (19:2). The advantages and disadvantages for this system are similar to the MMU and EEU, however, this system is more complex because it is a pressurized vehicle.

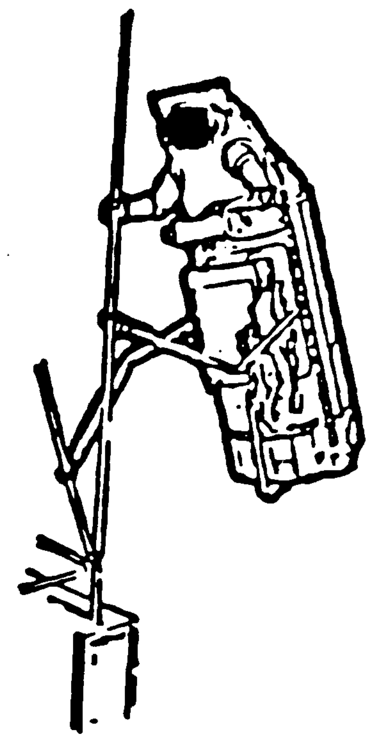


Fig. 29. Man-In-Can (19:1)

Manned Rover. This system is a maneuvering vehicle, operated by an EVA crewmember which can carry equipment in close proximity to the space station (Figure 30) (19:2). This vehicle is analogous to that of having a small tractor for use around the house. Again, the advantages and disadvantages for this system are similar to those of the MMU and EEU.

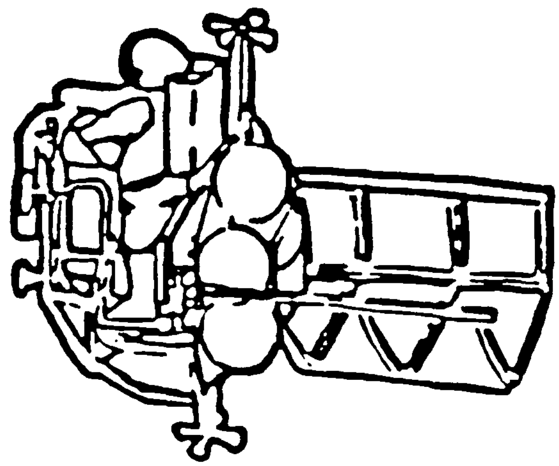
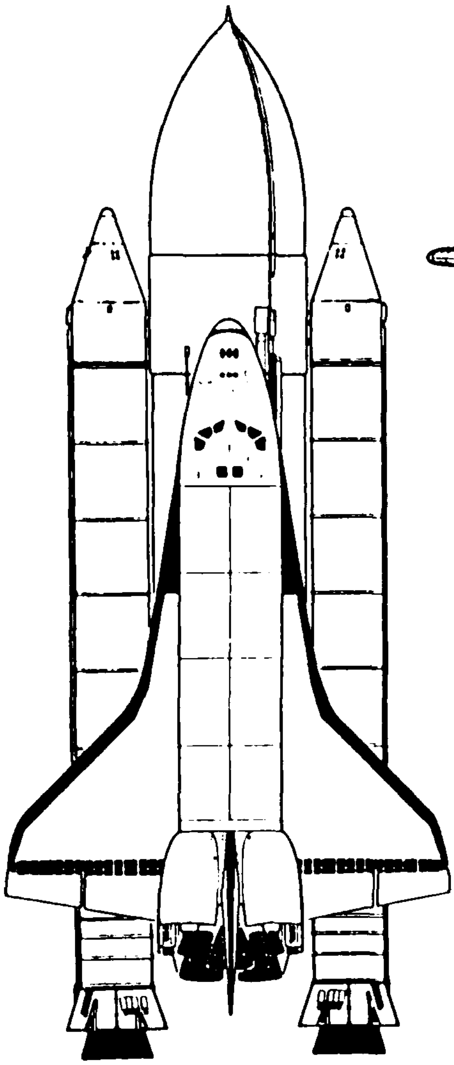


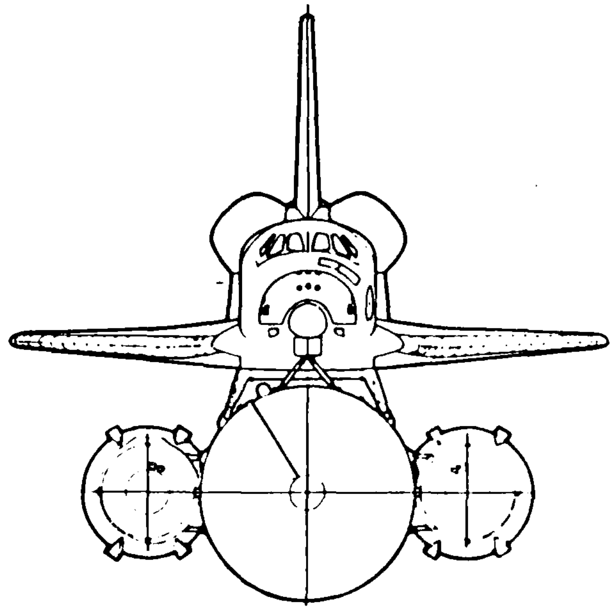
Fig. 30. Manned Rover (19:1)

Long Range Systems.

These systems were included in the thesis at the request of the NASA Space Station Office at Johnson Space Center (28). The description of the OMV is found in Chapter 5 of this thesis, the remaining systems are defined below.

STS. The Space Transportation System (aka. Space Shuttle) is the only proven recovery system. The shuttles design allows for the system to be flown to the vicinity of a drifting object (where either the Remote Manipulative System (RMS) or an EVA crewmember can grasp the object (see Figure 31). The advantages of this system are its reliability and proven space safety. Disadvantages include the fact that the shuttle will not always be present at the space station and that even if present at the space station, the shuttle may not be available for rescue/recovery operations.





ORBITER SPECIFICATIONS
Length: 121 feet
Width: 79 feet
Cargo Bay: 60 feet by 15 feet
Weight: 75 tons

EXTERNAL TANK
Height: 154 feet
Weight: 1.6 million pounds (full)

SOLID ROCKET BOOSTERS (SRBs)
Height: 149 feet
Weight: 1.3 million pounds each

Typical mission length: seven to thirty days
Typical crew: two to seven people
Height of orbit: 135-320 nautical miles (most missions)
Speed in orbit: 17,550 mph (at 150 miles)
Payload capacity: 65,000 pounds
Launch and landing sites: Kennedy Space Center, Fla.
Vandenberg Air Force Base, Calif.
Principal tracking station: White Sands, N.M.
Mission Control: Johnson Space Center, Texas

Fig. 31. Space Transportation System (6:13 3)

CERV (Crew Emergency Return Vehicle). This NASA space station program is designed to provide an emergency capability for astronauts at the space station to return to the earth. Still in conceptual development, several configuration are under study and are discussed below. Of primary concern with CERV is that it is designed to return crews to earth and is not designed for extensive space maneuvering. Major modifications to the systems would have to occur in order for them to accomplish rescue/recovery operations (8).

Discoverer, Gemini, AFE, MOSES, and 6 Man Apollo. These five configuration (Figure 32) are designed to re-enter the earths atmosphere and parachute to a safe landing. They are not designed specifically for space maneuvering (although they do have a limited Reaction Control System) and they have limited ability to grasp a drifting object (26:40). As such they would require significant modifications to allow for such rescue/recovery operations.

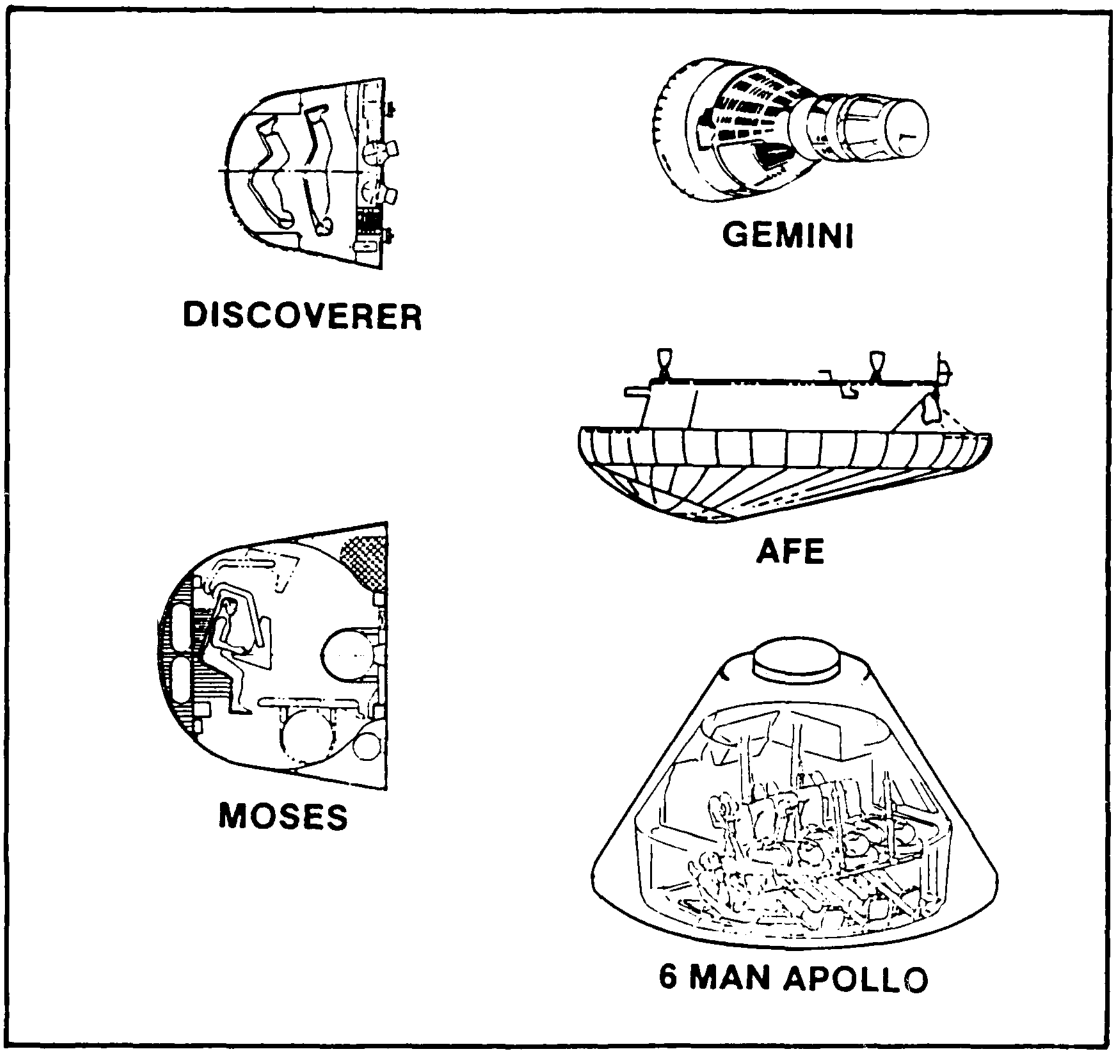


Fig. 32. CERV Systems (26:25)

Lifting Body Vehicles and LaRC (Langley Research Center) Configuration. These systems (Figure 33) are designed to land on the earth is a manner similar to the space shuttle. Again, limited maneuvering capability exists with these systems, as does the ability to grasp object.

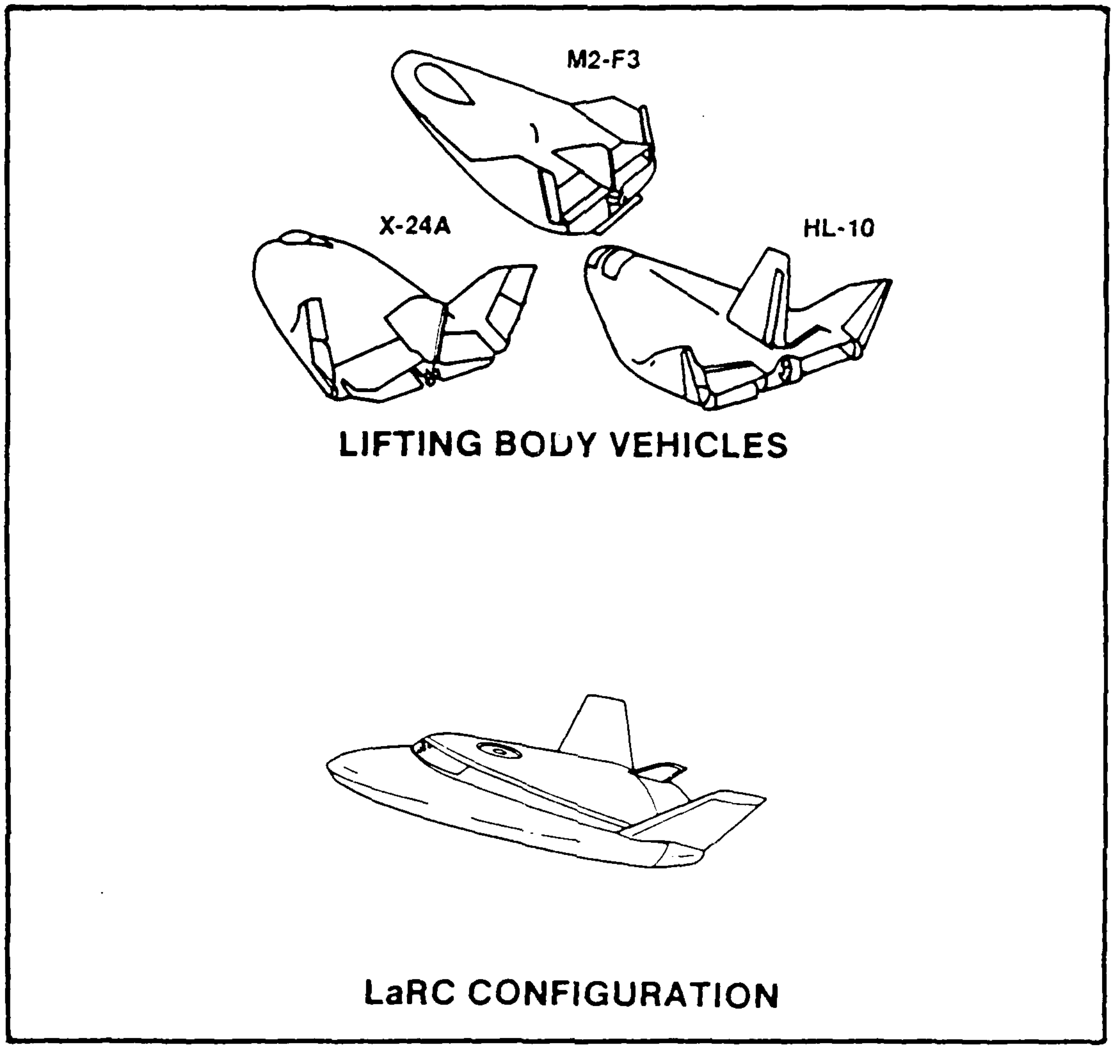


Fig. 33. CERV Lifting Bodies (26:25)

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This thesis is an analysis of the methods for EVA crew rescue and recovery of equipment detached and adrift from the space station. This top level analysis is aimed at identifying the proper direction to be taken in finding the solution system to the rescue/recovery problems. This analysis used the Hall morphology of systems engineering as the framework for the overall problem.

Within this approach, the technique of concept mapping was used to define the problem. Specifically, ten knowledgeable persons from Johnson Space Center were interviewed and a consolidated concept map of their understanding of the problems was generated. This map identified the key aspects and relationships between these aspects. Additionally, this map identified the evaluation criteria to be used in determining the preferred solution system to the problems.

The evaluation criteria of safety, response time, reliability, availability, and maintainability were used within the Analytic Hierarchy Process (AHP) to determine the preferred directions to take in solving the rescue/recovery problems.

Results of the analysis indicate that for short range rescue/recovery operations, both an EVA self rescue device and a space station supported device are the preferred solution systems. For medium range rescue/recovery operations, an unmanned free-flyer is the ideal solution system. Finally, for long range operations, the Orbital Maneuvering Vehicle (OMV) is the preferred solution. The analysis also showed that the combination of all these preferred solutions is needed to completely solve the problems. To this end, the analysis provides an example of a comprehensive rescue/recovery system. Finally, the analysis identifies issues and recommends areas which require further analysis in order to fully understand and solve the problems of EVA crew rescue and recovery of equipment detached and adrift from the space station.

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